A MULTI-ATTRIBUTE UTILITY APPROACH FOR EVALUATING ALTERNATIVE NAVAL AVIATION PLANS

DECISIONS AND DESIGNS INCORPORATED

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by

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SUMMARY

This report describes a multi-attribute utility approach to the development of an initial model for evaluating alternative naval aircraft weapon system (NAWS) force mixes. This evaluation model is being developed for use as a decision aid in formulating and supporting recommendations by the Commander, Naval Air Systems Command to the Chief of Naval Operations on programs for the Naval Aviation Plan.

The model is specifically designed to emphasize the difficult problem of inter-class trade-offs in terms of the utility of NAWS effectiveness. Each specific NAWS in a class is designed to handle one or more missions, and as inventory numbers of different NAWS in a mix vary, an associated variation in the utility of the mix can occur in one or more missions. Comparing the effectiveness of different systems performing the same mission is difficult, but far more difficult are inter-mission comparisons involving not only the technical question of capability but also the question of relative mission importance. Accordingly, inter-mission trade-offs are addressed in terms of operational preferences independent of considerations of system effectiveness, a procedure which thus simplifies the problem of inter-class trade-offs.

The model utilizes as inputs conditional measures of NAWS effectiveness. Effectiveness, as used here, is a function of the projected technical performance of the system in particular military missions against specified threats. A set of global scenarios is used to describe representative future situations in which the systems will be deployed. For purposes of analysis, these scenarios are partitioned into threat levels and missions in six geographical areas covering the world. The NAWS are introduced, and the utility of effectiveness in the scenarios is determined for each system by considering political and economic as well as military factors. Then the utility of a dynamic force mix is quantified over time by summing the expected utilities of the individual NAWS in the force during the time periods the system appears in the force inventory.

The initial utility model has been programmed in the interactive computer graphic facility at Decisions and Designs, Incorporated (DDI). To test the model, nominal inputs were utilized for four aircraft classes and four force mixes. The results of the test, included as an appendix to this report, show that the model produced the desired results by providing expected utility for NAWS force mixes in a form usable as an analytical decision aid.

Several advantages of the multi-attribute utility approach enhance its suitability for the air mix evaluation problem. Very important is the use of factoral decomposition procedures, which are of particular benefit in the assessment of inter-mission trade-offs in the utility of effectiveness. Also, the hierarchical structure which results from such an analysis provides an explicit and traceable logic, the complexity of which can be increased as the nature of the problem demands. Finally, computer implementation of the model on an interactive graphic terminal allows numerous, rapid sensitivity analyses which facilitate model modification and thus enhance model validity.

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ACKNOWLEDGMENTS

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ABBREVIATIONS

AEW	-	Airborne Early Warning
ASW	-	Anti-submarine Warfare
CILOP	-	Conversion in Lieu of Procurement
DDI	-	Decisions and Designs, Incorporated
MAU	-	Multi-attribute Utility
NAP	-	Naval Aviation Plan
NAWS	-	Naval Aircraft Weapon Systems
SLEP	-	Service Life Extension Programs
VAL	-	Light Attack
VAM	-	Medium Attack
VAQ	-	Tactical Countermeasures
VF	-	Fighter Class
VFX	-	Fighter Experimental

1.0 INTRODUCTION

The inventory of naval aircraft weapon systems (NAWS), supported by a dynamic systems acquisition process, changes from year to year. While some aircraft and weapons in service use are phasing out, others are in production, and advanced systems are in either conceptual or actual stages of development. Guidance for the naval aviation program planning and acquisition effort is given in the Naval Aviation Plan (NAP) by the Chief of Naval Operations and the Commander, Naval Air Systems Command. This plan undergoes continuous, iterative processing in harmony with the Navy's planning, programming, and budgeting process. The 20-year span of the NAP is sufficient to permit consideration of the long-term effects of near-term actions while remaining within reasonable technology and threat prediction limits. The key decisions in formulating the NAP involve time-phasing of the programs so that the highest quality and the required number of NAWS are maintained in the naval air forces within the constraints imposed by budgetary and other restrictions. Putting the plan together is a complex task, which requires a careful analysis of options and objectives.

The planning and acquisition process for naval aviation has been supported within the Navy by an excellent capability for technical analysis. Currently, developments in the decision sciences provide an accepted methodology for quantifying additional considerations, nontechnical in nature, which affect decision making. These methods enable the consideration of important qualitative variables, and the resulting analysis can understandably be more complete and relevant.

This report describes an evaluation model developed for purposes of assessing the utility of alternative naval aviation plans. Each alternative is an inventory mix of current and candidate follow-on weapon systems covering the 20-year period of the NAP. Every system can be described by a measure of effectiveness, varying with time, which is quantified by technical and operations analysis methods. The evaluation model considers these technical merits of the systems, their environment, and naval objectives to establish the utility of the alternative inventory mixes.

The evaluation model described in the following sections is the initial model, developed in the first phase of the planned work. The purpose of this first phase of the project was to develop a method for evaluating various combinations of inventories of NAWS which comprise viable force mixes for alternative NAP's.

Sets of viable inventory mixes addressed such alternatives as new systems, conversion in lieu of procurement (CILOP), or service life extension programs (SLEP). Before a specific recommendation could be made for the NAP, each mix needed to be assessed for cost versus benefit.[1]

The modeling of benefit, which was the principal work effort, had three objectives:

- Quantify expected utility by considering the relative benefits that accrue from employing NAWS in specific situations in different places as well as the associated probabilities of such employments;

- Allow valid inter-class as well as intra-class comparisons of systems; and

- Provide quick, economical, and supportable analyses of the alternatives.

The resulting model has been programmed on a digital computer with interactive graphic capability. Four mixes, each containing inventory numbers for four of the aircraft classes, have been used to test the model. The results of the trials will guide further development of the evaluation model and expansion of input data to all of the classes necessary to assess NAP alternatives.

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[1] Development of a model to assess benefits against costs was considered during the research effort. It was concluded that selected Navy cost models could provide adequate estimates of acquisition and life-cycle costs, that annual cost estimates for any force mix could be obtained by simply summing the individual system estimates, and that existing graphic presentation techniques for showing cost versus benefit could suffice for analytic assessments. This objective, therefore, was not pursued.

2.0 GENERAL METHODOLOGY

2.1 Objective

The main purpose of this research effort is to provide a mechanism for assessing the utility of alternative mixes of NAWS. As used in this report, the utility of a particular NAWS is the benefit obtained from having in the fleet those capabilities which are characteristic of that weapon system. The utility of a particular mix of systems is then defined as the aggregate benefit of such a force mix, and that utility must be assessed over time, in this case, the 20-year span of the NAP.

The utility of a mix of systems is dependent upon the effectiveness of that mix in each of the different missions that NAWS must perform. The total effectiveness of the mix of systems in turn depends upon the technical characteristics of each of the NAWS that comprise the mix. The military effectiveness of a particular system described by a particular set of technical performance characteristics depends on such factors as the nature of the threat to be faced in each of the missions the system must perform and the availability of support from other classes of air systems. For example, the effectiveness of a squadron of fighters in the fleet air defense mission against a low threat is different from the effectiveness of a squadron of fighters supported by an airborne warning and control system in the same mission against a high threat.

The utility of air system effectiveness in a mission varies as a function of the relative importance of the mission, and this importance depends on the potential consequences of not successfully completing the mission. The nature of these consequences and the utility associated with them in turn is dependent on such factors as threat intensity and the political and economic importance of an area. Furthermore, the nature of each of these factors varies over time. All these considerations emphasize the fact that the air mix evaluation problem is a highly complex one, and any model that adequately captures all aspects of the problem will also necessarily be very complex.

Nevertheless, it is desirable to develop a model which, although complex enough to capture the main aspects of the problem, is still manageable and provides a traceable path from variations in mixes to variations in mix utilities. It should also be the case that as more technically complicated questions are addressed, the model can be modified, either through increased complexity or through modified inputs to successfully answer these questions. It was with such an objective that the development of this initial model proceeded.

2.2 Methodological Overview

The air-mix evaluation problem consists of two sub-problems. The first is to predict the expected effectiveness of each of a large number of NAWS. The second is to assess the expected utility to be derived from various combinations of different NAWS.[1]

2.2.1 Predicting effectiveness - Since systems must operate in an uncertain future, any evaluation of these systems must consider the situations in which the particular systems are likely to be required to operate. This is accomplished by the utilization of a set of scenarios which describe situations representative of the future in which the systems will be deployed. This process is labelled "stage setting" in Figure 2-1.

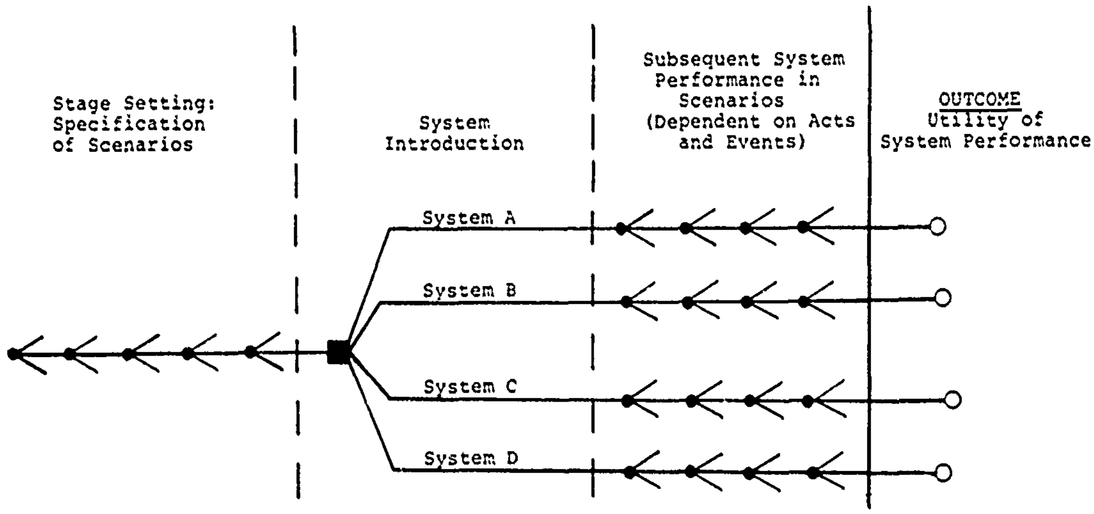

Figure 2-1: EVALUATION OF SYSTEMS TO BE DEPLOYED IN FUTURE TIME FRAMES

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[1]The general topic of the evaluation of complex systems has been recently addressed in two reports prepared by Decisions and Designs, Incorporated (DDI) under sponsorship of the Advanced Research Projects Agency. See Michael L. Hays, Michael F. O'Connor, and Cameron R. Peterson, An Application of Multi-Attribute Utility Theory: Design-to-Cost Evaluation of the U.S. Navy's Electronic Warfare System, Technical Report DT/TR 75-3 (McLean, Va.: Decisions and Designs, Inc., October, 1975); and Michael F. O'Connor and Ward Edwards, On Using Scenarios in the Evaluation of Complex Alternatives

Theoretically, once the stage is set, the systems are introduced, and their subsequent performances in the scenarios (dependent on relevant subsequent acts and events) are evaluated. The utilities of the resulting performances of the systems in the scenarios are weighted by scenario probabilities to yield expected utilities for the systems. However, since most of the systems are only paper systems and not prototypes for actual testing, the performance in scenarios must be predicted in some way.

One prediction method is the use of simulation models to simulate system performance based upon system specifications and scenario details. Such simulations can be quite costly, and using them when there are many systems or many scenarios can be prohibitively expensive. The simulation models also often involve assumptions about the subsequent acts and events indicated as relevant to performance in Figure 2-1. The nature of such assumptions is not always clear simply because of the complexity of the simulation model; that is, the complexity of the model often makes the process by which input measures lead to output performance untraceable. Despite these potential drawbacks, however, simulations can provide excellent analogues to the actual physical processes that determine output effectiveness.

A second approach to performance prediction is to develop a less complex model which relates system technical performance characteristics or system specifications to measures of performance. System performance is sequentially partitioned into more specific subsystem performances until a highly specific level of technical performance characteristics is reached. These technical performance characteristics can be as specific as actual engineering design parameters or as general as NAWS characteristics like reliability and availability of weapons, missile lethality, radar detection range of a particular weapon system; capability of built-in combat direction logic; and the like. These characteristics can be obtained through expert judgment, subsystem performance simulations, or other prediction mechanisms.

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[1](cont.) Technical Report 76-17 (McLean, Va.: Decisions and Designs, Inc., forthcoming). Together these two reports provide an in-depth discussion of the general topic of the evaluation of complex systems and of the specific topic of multi-attribute utility models. The interested reader might wish to consult these reports as a methodological supplement to this report on the application of multi-attribute utility (MAU) assessment procedures.

Whatever the approach, be it performance simulation or some variation of a factoral decomposition procedure, highly specific design parameters of aircraft weapons must be related to more general measures of system effectiveness. As illustrated in Figure 2-1, such general measures are dependent on the scenario specification. Put differently, expected performance is a conditional measure, dependent on the actual conditions in which the system will perform.

This critical part of the air mix evaluation problem is normally handled through technical assistance from naval laboratories which provide the necessary effectiveness estimates. For model purposes, a set of missions is specified, each mission involving only one aircraft class, fighter, for example. For each possible mission of a NAWS there exists a corresponding reference NAWS, a fully modern system of the baseline year, FY 1976. These reference NAWS may have recently gone into fleet service and as a result are essentially "state-of-the-art" systems. Thus, the reference systems will be a set of the most capable systems which are in the fleet in the baseline year, FY 1976.

Any particular system to be evaluated is compared to the reference system for the mission that the specific system carries out. Multiple-mission NAWS are compared to the reference NAWS in each of the multiple missions. The reference systems thus provide intra-class anchors for effectiveness assessments. The technical effectiveness of a NAWS in a mission is expressed as percent of the effectiveness of the reference system for that mission. These effectiveness measures are normally provided by Navy technical sources. Also provided are all assumptions upon which the measures were conditionally assessed, such as levels of threats, levels of support from other NAWS, and the like.

2.2.2 Assessing utility - The fact that the effectiveness measures capture the technical performance aspects of the evaluation problem points out a difference between the air mix model and several other evaluations performed by DDI. In a number of previous analyses,[2] the technical performance

[2] James O. Chinnis; Clinton W. Kelly, III; Rex D. Minckler; and Michael F. O'Connor, Single Channel Ground and Airborne Radio System (SINCGARS) Evaluation Model, Technical Report DT/TR 75-2 (McLean, Va.: Decisions and Designs, Inc., September, 1975); and Hays, O'Connor, and Peterson, op. cit.

characteristics of the system were used as inputs upon which to base judgmentally simulated performance and thereby formulate technical system utility assessments and operational acceptability assessments. Military utility was then established by considering these and other factors.

The utility models resulting from these studies assess military utility from a predominantly technical point of view. How well does the system do what it should do? How operationally acceptable is it? What is its growth potential? Assessing the military utility of one electronic warfare system aboard a destroyer compared to another designed to do essentially the same thing is a technical problem, one that can be fairly independent of nontechnical factors such as political, geographical, and socioeconomic considerations. Such models are structured to specify the most cost-effective system that can handle the threats in the scenarios.

The NAWS force mix evaluation approach takes as given the relative effectiveness of the air systems. A particular mix of NAWS is, therefore, a multi-attributed alternative where an attribute is defined as effectiveness in a particular mission. The effectiveness in a specific mission is directly related to the effectiveness of the NAWS in the particular class of systems that performs that mission. The major factor involves how effectiveness can be traded off between and within classes. This trade-off depends not only on the threat levels in areas of the world but also on other considerations such as the importance to the United States of a good outcome in a particular scenario. The force mix evaluation must, therefore, address political, geographical, and socioeconomic considerations as well as more high-level policy considerations than are required in strictly technical system evaluations.[3]

The air mix evaluation model, then, serves as a mechanism for transforming the set of effectiveness measures that describe a particular mix of NAWS into a valid utility

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[3]The reader familiar with the multi-attribute utility (MAU) approach will find a slight difference in the discussion of the approach in this report. The typical emphasis on hierarchical decomposition is not made here. Rather the decomposition is approached from the point of view of developing a method for taking a matrix of input technical measures for air systems and modifying that matrix to yield utility measures for those systems. The approach, although appearing to be procedurally different, is nonetheless theoretically the same.

for that mix. Utility is based upon the value of each system, in the missions it can perform, against appropriate threat intensities, in scenarios, and in relation to the politico-military environments in which U.S. forces are likely to operate.

Theoretically, each alternative mix of specific NAWS must be evaluated in each scenario in order to fully account for any interdependencies among the specific NAWS in an air mix. Since eventually there will be a large number of NAWS, and since there are already a large number of years, the resultant evaluation would be prohibitively detailed because of the large number of mixes.

An alternative to evaluating each air system in all scenarios is to pull only the set of reference NAWS, one for each mission, through the scenarios to establish weights to be assigned the NAWS that perform those missions. These weights would be combined appropriately with effectiveness measures to provide utilities for alternative mixes of NAWS. This approach is illustrated in Figure 2-2.

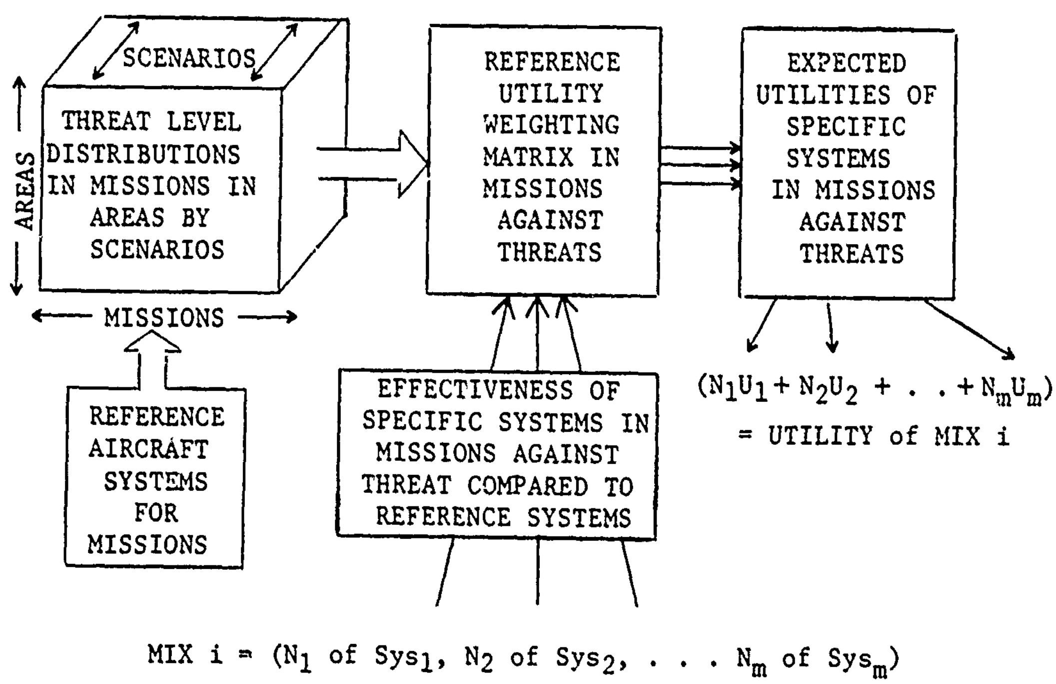

Figure 2-2: MODEL FOR ASSESSING NAVAL AIRCRAFT WEAPON SYSTEM FORCE MIXES

As indicated, the output of the evaluation of the reference systems in scenarios is a weighting matrix for NAWS in missions against threats. The matrix is scenario-independent, and the weights are applied to the technical effectiveness measures for specific NAWS in missions against threats. Systems other than the reference systems, then, need not be evaluated in each scenario, and the expected utilities of alternative mixes can be established quite easily given the validity of the output reference utility weighting matrix.

General procedural steps in the evaluation can be summarized as follows:

- o Specify the nature of missions, threats, and world areas;

- o Develop scenarios which validly represent the future in which NAWS mixes will operate. Such scenarios describe the specific action type, threat levels, and other relevant details for all areas of the world;

- o Specify reference NAWS for each mission to be performed. A specific mission is performed by one specific class of NAWS. A system can perform more than one mission;

- o Evaluate the utility of reference NAWS effectiveness in each scenario. Such evaluation involves inter-mission trade-offs in terms of the utility of effectiveness of the reference NAWS. Is it more desirable to have strong VF (fighter) systems or strong VAM (medium attack) and VAL (light attack) systems in this scenario? The utility trade-offs obviously must involve mission importance which, in turn, depends on the magnitude of the threats faced, the importance of actions in different areas of the world, and the like;

- o Combine reference system utilities across scenarios to yield the reference utility weighting matrix for NAWS in missions against threats. This matrix is scenario independent; and

- o To evaluate a particular mix of specific NAWS, input into the weighting matrix numbers and effectiveness measures of the specific NAWS in each class for that mix. This process is illustrated in the middle section of Figure 2-2. The outputs of the matrix, the expected utilities of specific systems in missions against threats, are multiplied by the appropriate numbers of specific systems and summed to yield an expected utility for the mix.

The validity of this procedure and the resulting output model depends on the validity of several methodological simplifications. These simplifications and alternative approaches will be discussed in the more detailed discussion of model development which follows in Sections 3.0 and 4.0.

3.0 SPECIFICATION OF MISSIONS, THREATS, WORLD AREAS, AND SCENARIOS

The purpose of the modeling effort is to develop a mechanism for establishing the relative utilities of having the effectiveness values associated with different NAWS. A potential model output would be that the expected utility of having the effectiveness of a particular VF system is several times the utility of having the effectiveness of a particular VAL system. It is, therefore, necessary to identify those critical variables upon which such utility trade-offs are dependent. There is, of course, a potentially large set of such variables, but in order to provide a manageable evaluation system, this set must be restricted to the three or four variables which are associated with most of the variance in the utility of alternative mixes of systems. Those conditioning variables identified as critical are missions, threats, world areas, and scenarios.

3.1 Missions

A major goal of the force mix evaluation model is to establish inter-class air system trade-offs. Intra-class comparisons, such as F-4 versus F-14 (VF systems) have been accomplished. However, inter-class trade-offs, for example, F-14 versus A-7E (a VAL system) are more difficult to make, for the task is one of comparing options that have different purposes, options which, therefore, are not easily comparable.

Six missions were selected for use in the initial model. They are:

- LAND-BASED ANTI-SUBMARINE WARFARE (ASW) - Includes employment of land-based NAWS in surface and subsurface surveillance operations; and search, intercept, and destroy operations against submarines in broad ocean and coastal areas.

- SEA-BASED ASW - Includes employment of ship-based NAWS in surface and subsurface surveillance, barriers, search, intercept, and destroy operations within a tactical radius of the ship.

- FLEET AIR DEFENSE - Includes employments, such as combat air patrol and deck-launched intercept units against actual or potential enemy strikes by aircraft and air, surface, or submarine launched offensive missiles.

- ESCORT - Includes employment of airborne fighter units in defense of our own strike forces in the vicinity of targets and of entry and exit routes.

- DAY/NIGHT VISUAL ATTACK - Includes visual bombing or guided weapon delivery in strikes, armed reconnaissance, defense suppression, and close air support, generally under predominantly visual conditions enroute.

- ALL-WEATHER ATTACK - Includes radar delivery of weapons in nonvisual weather, generally under predominantly non-visual conditions enroute.

The number and kind of missions which eventually should be considered in evaluating the entire NAWS will likely differ from the six which have been used in the initial model. Also, the model is initially limited to consideration of effectiveness in three missions for individual systems ossessing multi-mission capability. These arbitrary choices in no way void the methodology utilized in this evaluation. It is a simple matter to redefine and expand the mission categories, and no change to the computer program or algorithm is required. Given adequate computer capacity, sufficient flexibility exists to address the problem of evaluating, within the existing framework, all of the NAWS likely to be encountered in the NAP.

3.2 Threats

Three generic threat levels were considered sufficient for the final structures of the evaluation model. A review of several Navy studies showed that threat was defined in almost all cases by four characteristic categories: systems quality, numbers in forces, tactics, and the level of potential damage that could be inflicted by the threat forces. The generic threat levels are defined in Table 3-1 below.

The threat levels are necessary both for developing utilities and for classifying the level of opposition which naval air forces may face in the global scenarios. The modeling work indicated that it is feasible to classify enemy forces in each world area according to the three levels selected.

As indicated, the threat levels mix numbers and technology. Although it is reasonable to assume that numbers and technology are correlated, some cases will involve only a few very sophisticated systems of high quality, and other cases will involve large numbers of systems of low quality. A more extensive analysis would address additional threat levels by considering the different combinations of numbers

THREAT	CHARACTERISTICS			
	SYSTEMS QUALITY	NUMBER IN FORCES	TACTICS	POTENTIAL DAMAGE
HIGH	Complex, Highly Effective, Powerful	Large	Very Well Coordinated	Grave Losses
MEDIUM	Mixed	Modest	Fair	Moderate Losses and Damage
LOW	Weak, Unsophisticated, Low Performance	Small	Fair to Poor	Little or None

Table 3-1: Generic Threat Definitions

and technology of systems. However, the three threat levels described here seem sufficient for a first approximation to demonstrate the ability of a model to discriminate effectively among NAWS mixes in terms of utility.

3.3 World Areas

The technological capability of a NAWS does not change with area of the world. But the probable threats, as well as the importance of countering the threats, does depend on area of the world and timeframe. Likewise, inter-mission trade-offs can depend on these variables. It is, therefore, assumed that the utilities of alternative mixes are area-dependent, and area is inserted in the model as a conditioning variable, that is, a variable upon which utilities are dependent. The use of areas is also a convenient device for partitioning the future world into scenarios. The assessment of the probability of facing different levels of technical threats, a difficult if not impossible global judgment, can be greatly facilitated by considering specific world areas.

For use in the model, six maritime areas were selected, each area including littoral countries. Each area has an acceptable degree of politico-military cohesiveness and a uniformity of importance in terms of U.S. interests. The boundaries of the areas are shown in Figure 3-1.

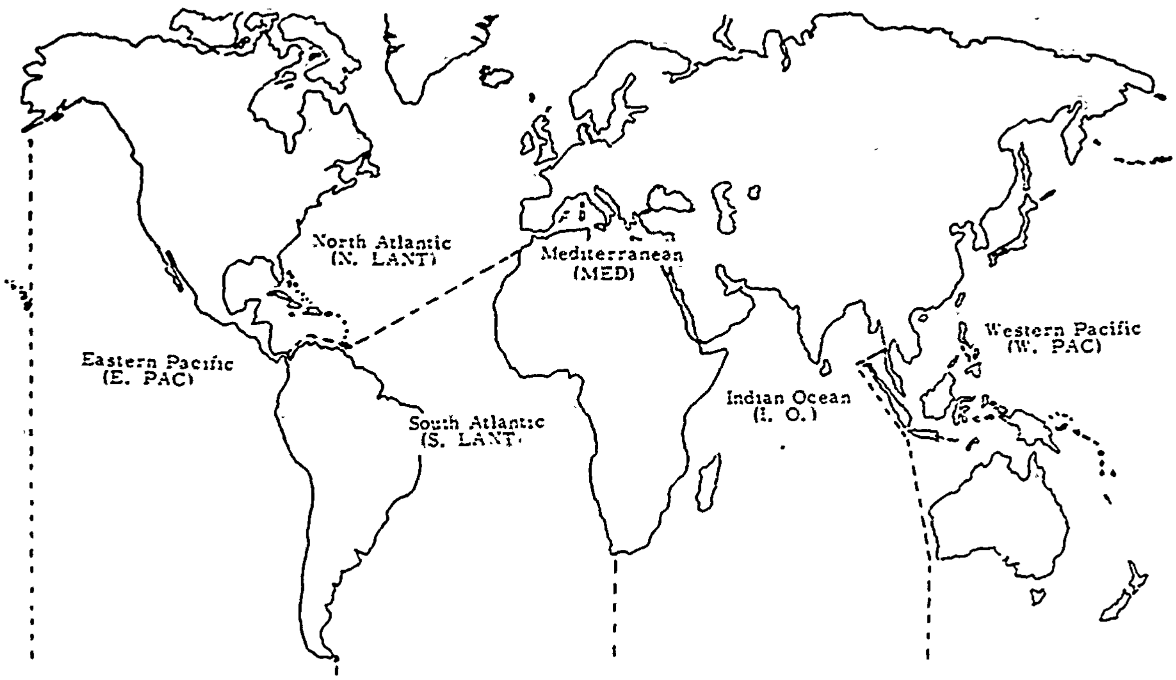

Figure 3-1: WORLD AREA BOUNDARIES

3.4 Scenarios

Since military system evaluations involve systems to be deployed in an uncertain future environment, evaluation must be conditional upon educated assessments of the possible future situations in which the systems must operate. To solve this problem, evaluation is made within the context of scenarios which, hopefully, capture all aspects of the future relevant to utility assessments.[1]

Crucial in any evaluation effort, scenarios must have two properties in order to be effective: first, they must validly represent the future situations; and second, they must discriminate among the systems in terms of utility (if such discrimination is possible). Theoretically, a large

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[1] O'Connor and Edwards, op. cit.

number of precise scenarios is desirable to obtain precise, stable utility estimates. Precise scenarios should capture the major amount of variance in utility for each system and at the same time be representative of the future world. The necessity for a valid representation of the future world should be obvious from the viewpoint of both design and evaluation. A system should be designed to emphasize those threats likely to be encountered. Similarly, specific designs should not be eliminated from among several proposed systems because they are unable to handle certain contrived scenarios that are in essence "unreasonable" representations of the future world.

Since many details can cloud the judgmental process and lead the expert to attend to details that are irrelevant for ascertaining the difference in utilities of proposed designs, excessive detail in scenarios should be avoided. At the same time, however, the scenarios must contain those aspects of the future that discriminate among the different proposed systems in terms of utility. For example, it may be the case that all the systems handle the fairly likely scenarios, and that the real differences among systems occur for several aspects of system design that will only be emphasized by certain kinds of possible future threats. These threats, then, should be contained in reasonable form in one or more of the scenarios used for evaluation.

These two properties of sets of scenarios, representation and discrimination, though extremely important, are not necessarily compatible. Moreover, since large numbers of highly specific scenarios lead to very expensive and tedious evaluations, compromise on the number of scenarios is usually necessary. In order to ensure a limited number of high-quality scenarios, the expert is asked to isolate those aspects of the future world that discriminate in terms of utility among alternative NAWS mixes. In this analysis, such aspects include threat levels, areas of the world, situation (noncrisis or deterrence, crisis, unilateral military action, and conventional war), and time. The multi-attribute utility analysis establishes conditional expected utilities by using assessments dependent upon these conditioning variables.

The scenarios selected for use in the evaluation model are shown in Table 3-2 below. Likely combinations of conflict and nonconflict situations are covered.

	SCENARIO														
	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
N. LANT					C				W				C		
W. PAC			C						W	C U	U				
I.O.				C		C	U					U			U
MED		C				U	U	U	W			C	C		
S. LANT													U		
E. PAC														U	

SITUATION ABBREVIATION: Blank - Deterrence (Noncrisis)
C - Crisis
U - Unilateral Military Action
W - Conventional War

Table 3-2: Scenarios

The situations in areas are described as follows:

- WAR - A global conventional war involving the United States and its allies, and the Soviet Union and its allies;
- UNILATERAL MILITARY ACTION - A unilateral military action involving combat engagement of U.S. forces, ith no direct opposition by the Soviet Union or the Peoples' Republic of China;
- CRISIS - An employment of U.S. forces short of combat to support national objectives during regional or local conflict, confrontation, or political instability; and
- NONCRISIS - Maintenance of freedom of the seas and international airspace by a U.S. presence.

These scenarios were developed in an earlier DDI research effort on the analysis of the value of aircraft carrier and non-carrier alternatives.[2] Because sea-based naval aviation is aboard carriers, the threats faced by the task force and the NAWS are described by the same scenarios. The actual use of these scenarios is discussed later in the report.

[2] See Decisions and Designs, Inc., A Decision Analysis Method for Assessing the Value of Aircraft Carriers and Non-Carrier Alternatives.

4.0 METHODOLOGICAL DETAILS OF MODEL DEVELOPMENT

In this section, the derivation of the model is considered step by step. Assumptions made in that development are discussed in detail.

4.1 The Use of Reference Naval Aviation Weapons Systems to Obtain the Weighting Matrix

An alternative to the prohibitive task of evaluating each NAWS force mix in each scenario is to evaluate only the reference systems in the scenarios. Other NAWS, instead of being evaluated in the scenarios, are given values related to the utility assigned the appropriate reference system as result of evaluation of the reference system in the scenarios. If undertaken, the quality of the resulting approximations is dependent on the validity of several assumptions.

It is assumed that effectiveness measures are scenario-independent; that is, the technical effectiveness of an experimental fighter (VFX) as compared to the reference system for the VF class remains constant for scenarios and is dependent only on threat. This assumption is likely to hold because the effectiveness measures are a function of technical performance characteristics that are scenario-independent.

Consider the following hypothetical air mix consisting only of VP and VAL systems in Table 4-1.

INVENTORY	SYSTEM	EFFECTIVNESS
N_1	VP_1	.8
N_2	VP_2	.5
N_3	VAL_1	.9
N_4	VAL_2	.7

Table 4-1: Hypothetical Mix of VP and VAL Systems

The utility assigned VP_1 will be .8 times the utility of the reference VP. Similarly, the utility assigned VP_2 will be 50% of that of the reference VP. The respective utilities of VAL_1 and VAL_2 will be 90% and 70% of the utility of the reference VAL system.

In order for this approach to be a valid one, it must be the case that if this mix were evaluated in each scenario and the utilities were aggregated across scenarios, the resulting utility of the VP_1 system would be 80% of the utility of the reference system for the VP class. Likewise, the resultant utility of the VAL_2 would be 70% of that of the reference system for the VAL class. Note that this does not say that the VAL_2 would receive 70% of the utility of the reference VAL air system in each scenario, but rather that such a result would be the expected average. In other words, the assumption is that deviations in utility around the 70% mark will average out across scenarios.

Several conditions help to ensure the quality of the approximation. One is that utilities of effectiveness as a function of threat and mission are not markedly non-linear. If, for example, a NAWS must have 80% of the effectiveness of the reference system in order to have any military utility at all, the quality of the proposed approximation is likely to be lessened. However, in the development of the model, the realistic assumption was made that one or more squadrons of each type of NAWS would be involved in any action, and the numbers of NAWS would negate any effect of the kind mentioned. In other words, a squadron of VAL_2 would be about 70% as effective as a squadron of VAL reference systems.

4.1.1 Interdependencies among naval aviation weapons systems - Another aspect of the problem that helps to ensure the accuracy of the proposed approach is the existence of certain independence conditions. Few or minimal synergism or antagonisms should exist between NAWS performing different missions. For example, it should not be the case that a particular VAL system has a higher effectiveness and associated utility when combined with one VF system than it does when combined with other VF systems. Rather, the effectiveness and utility trade-offs that exist should be among the reference systems for the respective NAWS classes that perform the different missions. If a particular VAL system paired with one VF is 70% as effective as its reference system and paired with another VF is only 50% as effective as its reference system, then the desired independence condition fails. Similarly, more complicated violations of independence can occur. For example, the trade-offs between two classes, say the VAL and VF classes could depend on the level of AEW (airborne early warning) support available in the mission.

The violations of independence conditions discussed are not unlikely to occur. Such violations complicate the assessment problem, but they do not invalidate the given approach. If the utility trade-offs or effectiveness measures required vary as a function of different combinations of NAWS mixes, then they can be assessed conditional on these. As indicated, effectiveness measures provided by Navy technical sources are dependent on a specific set of assumptions. To account for more complex dependencies, several sets of assumptions can be furnished the technical sources, and effectiveness measures conditional on each can be assessed.

The only real problem with potential violations of independence is the number of them. The purpose of developing a model is to provide a general mechanism for decomposing the evaluation problem. If the dependencies are so complex that effectiveness measures for each NAWS must be assessed for each mix, little has been gained. For the missions under consideration, this is not the case.

For the six missions listed in Section 3.1, the trade-offs between any two classes generally do not depend on the effectiveness level of a third class, and the approximation utilized is quite likely to be valid here. As the model is expanded to cover all missions, the effectiveness of systems in missions does depend on the level of effectiveness of NAWS in direct support missions. However, the number of such supporting systems relevant to any trade-off or effectiveness assessment is small, and the problem can be handled as indicated. Effectiveness measures and trade-offs are assessed conditional on the level of support in these missions. For any particular mix, that level of support will be the level provided by th specific air systems in that mix. Given that level of support, the appropriate effectiveness values can be inserted in the model.

The actual expansion of the model to cover all missions may involve decomposing certain missions. For example, the strike escort mission could be divided into short- and long-range strike escort. In long-range missions, or in situations requiring the VF system to remain at station for long periods, fuel support must be provided by tankers. The same is true for the VAL and VAM systems involved in strike missions. Similarly, in the strike missions, the tactical countermeasures system (VAQ), which provides electronics support and jamming enhances the capability of the VF system. In the fleet air defense mission, the airborne early warning system (AEW) serves to detect threats at long range and to control the interception of the target and thus enhances the capability of the VF in this mission.

These additional systems can be introduced and the model expanded to accommodate the dependencies that result. There are few other system classes that are relevant to the problem, and the complications that occur, therefore, do not require so many additional assessments as to greatly reduce the usefulness of the approach. Put quite simply, a complete treatment of the problem requires an expanded model that is conceptually the same as the prototype developed here. Prior to such an effort, the potential usefulness of the prototype can, of course, be demonstrated.

4.1.2 Threat-dependent effectiveness measures - Another requirement for the validity of this approach concerns the nature of the effectiveness measures. As indicated, these measures must be conditional on mission and threat and must be based on a comparison to the reference systems. In addition, these measures must not contain considerations of utility since they could lead to double counting in parts of the problem.

The point concerning double counting illustrates the significance of the effectiveness measures as well as the importance of interpreting them accurately. In early stages of this investigation, curves such as those displayed in Figure 4-1 were considered and their use rejected. Here the utility of the percentage effectiveness of three VF systems compared to the reference VF system (100%) is plotted. The assumption is that for a high-threat situation, in which a NAWS needs all its capability, this utility is linear with percent effectiveness. However, for a low-threat situation, only a small percentage of the effectiveness of the reference system is needed, and therefore the utility curve rises rapidly and asymptotes.

While these curves appear to be reasonable, they would in essence double count information unless the percentage effectiveness measures are threat independent. The technical centers, however, provide effectiveness measures for each system as compared to its reference system as a function of threat level. This purely technical consideration already accounts for the aspect of the problem illustrated by the curves in Figure 4-1. These threat dependent assessments are requested because they are more meaningful. To assess the percentage effectiveness of a fighter, for example, compared to the reference fighter independently of threat level would require a difficult intuitive aggregation across the factors specified by threat level. Such aggregation is extremely difficult and would likely lead to questionable measures.

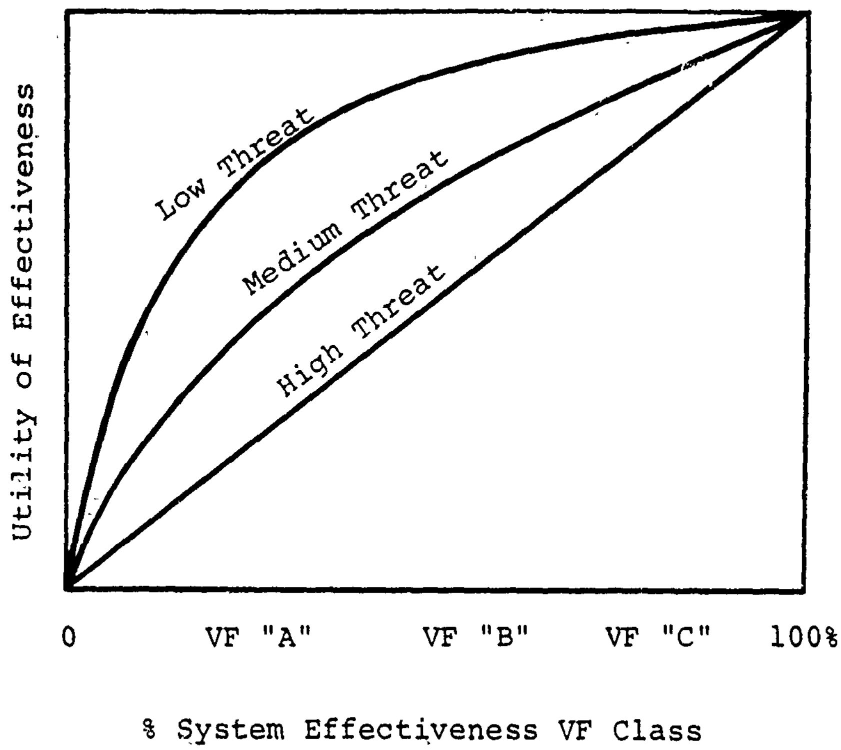

Figure 4-1: UTILITY OF EFFECTIVENESS FOR NAVAL AIRCRAFT WEAPON SYSTEM IN THE FIGHTER (VF) CLASS

4.2 Utility of Reference Systems in Deterrence

The goal of the decomposition of utility judgments is to identify a set of conditioning variables upon which the utilities of NAWS are dependent and with respect to which meaningful utility trade-offs can be assessed. One obvious variable is the scenario in which NAWS is deployed. A set of 15 scenarios structured to include the desirable properties discussed in Section 3.4 decomposed the utility assessment problem into 15 more specific sub-problems. In order to maintain a linkage between scenarios in terms of a unit of measurement, the most likely scenario, that of worldwide deterrence (non-crisis), was chosen as a standard for calibration purposes, for in every scenario the Navy is involved with deterrence in some area(s). The utility of effectiveness in the different deterrence missions provides a consistent unit of measurement across scenarios. That base utility takes on the same value in each scenario.

4.2.1 Operational trade-offs of mission effectiveness - A credible military capability is requisite to successful deterrence. Since NAWS are one of the means of achieving deterrence, it is reasonable to assume that the extent to which these systems achieve credibility in deterrence is equivalent to their ability to accomplish their combat missions. In other words, the effectiveness required of the systems is the same in a deterrence scenario as it is in a combat scenario. However, the expected utility of that effectiveness is greater in an actual combat situation because the necessity of accomplishing the job is a certainty. That is, the threats being deterred are actually being faced in combat. Thus, it is sufficient to determine the utility of systems in deterrence, Scenario 1, and adjust that utility for the seriousness of the more specific situations in other scenarios and the likelihood that they will occur. The initial step in implementing this approach is to derive the utility of the reference systems.

Since the inter-class trade-offs are one of the major goals of this derivation, and since these depend on utilities in missions, it is imperative that decomposition of the problem into component judgments made for given missions and threat in no way mask or distort these trade-offs. The variance in utility that the model seeks to capture is this variance of inter-class utility. It is quite possible to partition the judgment problem to the extent that the trade-off judgments become difficult or impossible. For example, in high-threat situations, more VF effort must be expended on fleet air defense and escort, whereas in low-threat situations, less VF effort can be expended on these missions. Therefore, threat level within mission is a conditioning variable of major importance. To ask an expert to judge the relative utilities of effectiveness in missions by judgmentally aggregating across threats would be to encourage an invalid response. Accordingly, the inter-mission utility judgments were made conditional on each of the three threat levels described in Section 3.2.

A typical judgment would be the following. If the utility of the effectiveness of the reference NAWS in the fleet air defense mission against a high threat is X, then the utility of the reference system in the day/night visual attack mission against a high threat is Y. Note that this is essentially a technical trade-off. Given a high threat, what are the relative utilities of the effectiveness of each of the reference NAWS for each mission? What are the utilities for the effectiveness of each of these systems against a low threat?

The direct trade-off of the relative utility of the effectiveness of a reference system against a high threat in one mission is not directly compared to the utility of the effectiveness of a different reference system against a low threat. However, the importance of countering the threat is a function of threat level. Therefore, the inter-mission utilities of effectiveness must be differentially weighted for different threats. Note that one method for differential weights is to have the expert set the utility of effectiveness of the reference VF at some value, say 100, for the high threat and judge the utilities for the medium and low threat by comparison to the high threat. The same can be done for the other missions. This procedure would seemingly account for the different importances of threats.

A subtle problem occurs with such a procedure. Recall that the inter-mission utility trade-offs are assessed dependent on threat level. If the inter-threat utility trade-offs are then assessed as a function of mission, the problem of double counting occurs, for certain of the same considerations that led to inter-mission trade-offs will be involved in inter-threat trade-offs. Put simply, either the inter-mission trade-offs must be threat-dependent and the inter-threat trade-offs mission-independent, or vice versa. Since the inter-mission trade-offs were of major concern, these were assessed as threat-dependent, and the expert was then asked to judge the importance of countering each threat level across missions.

Accordingly, the utilities in the deterrence scenario were assessed by first considering the utility of effectiveness in missions as a function of threat. Since the number 100 is a convenient base for making comparisons, all utilities were set at 100. Then the relative inter-mission trade-offs of utilities of effectiveness were assessed. The initialized matrix is illustrated in Table 4-2.

MISSION / THREAT	L-B ASW	S-B ASW	FAD	ESS	VIS ATK	A/W ATK
High	(100)	(100)	(100)	(100)	(100)	(100)

Table 4-2: Relative Mission Importance for High Threat

The expert is advised to keep the definitions of the missions and the high threat firmly in mind and then asked which of the missions has the most importance. The utility of effectiveness for the most important mission is defined as 100. The expert is next asked to modify the utilities for other missions downward to reflect relative utilities of effectiveness in missions. The expert is next asked to provide utility judgments across missions for the medium threat, and then for the low threat.

The relative utilities in missions for each threat level are normalized to sum to 600. This procedure preserves both the sum of the blocks as it was at the beginning and the expectation of 100 for any cell. The relative utilities of effectiveness for the missions are then displayed in a single matrix, with the format shown in Table 4-3.

MISSION / THREAT	L-B ASW	S-B ASW	FAD	ESS	VIS ATK	A/W ATK	SUM
H							600
M							600
L							600
							1800

Table 4-3: Relative Mission Importance for Threat

At this point, the numbers in the matrix can be inspected by the expert, and modifications can be made. However, such modifications are restricted to intra-row threat dependent inter-mission trade-offs. Whenever one or more changes is made in a particular row, the entire row is renormalized so that entries sum to 600. At this point, comparisons across rows would be meaningless because the relative importances of different levels of threat have not yet been assessed.

Once the utility of effectiveness relationship among missions is established, the next step is to determine the general utility relationship among threat levels. The elicitation can be direct and use the display shown in Table 4-4. Since the consequences of failure to accomplish missions are so serious, the utility of system effectiveness is assumed to be highest for the high-threat level, which is set at 100.

THREAT	
H	(100)
M	
L	

Table 4-4: Relative Importance of Countering Threat

The expert is first advised to consider the relative losses associated with mission failure; he is then asked to confirm a utility of 100 for the high threat or assign 100 to another threat level at which the need for and importance of effectiveness is greatest. The expert is next asked to assign equal or lower utilities to the other threat levels to complete the matrix.

Multiplying the matrix shown in Table 4-4 by the corresponding row in the display in Table 4-3 results in the relative utility of the reference systems in terms of mission and threat in Scenario 1, deterrence. Again, the resulting matrix, shown in Table 4-5, is renormalized, this time to sum to 1800, so that the expectancy in any cell is 100, and the differences among cell entries reflect relative differences in the utilities of effectiveness in missions against threats.

MISSION / THREAT	L-B ASW	S-B ASW	FAD	ESS	VIS ATK	A/W ATK
H						
M						
L						
	(Sum = 1800)					

Table 4-5: Weighted Relative Mission Importance

The numbers in the matrix illustrated in Table 4-5 may be inspected and modified by the expert. The interactive computer graphic capability permits any changes to be easily made. However, such changes are restricted to changes in the matrix in Table 4-3, the threat dependent inter-mission trade-offs, or changes in the matrix in Table 4-4, the inter-threat comparisons. First priority is given the inter-mission trade-offs.

Note that this procedure will likely lead to more iterations than a procedure which allows direct modification of the matrix in Table 4-5. Such direct adjustments could be allowed, and the matrix could be renormalized to sum to 1800 after each adjustment. This procedure was not employed for the same reason that the 18 matrix cell entries were not initially directly assessed to allow simultaneous inter-row and inter-column comparisons. Double-counting problems and related problems with changing, unspecified decision criteria are likely to occur in such a process. The decomposition approach, although slightly more time consuming, is designed to reduce the probability of such problems.

The final display, shown in Table 4-5, shows the utility of reference systems in deterrence in a strictly generalized sense limited to general operational factors. Universal in nature, the matrix should contain only considered judgments of operational experts. Since political and economic factors affect the relative value of effectiveness in mission, it is necessary to consider these next.

4.2.2 Political and economic considerations--the use of areas - As indicated, another conditioning variable to which the utility of effectiveness is sensitive is the area of the world in which an action takes place. In this analysis, areas of the world are structured in terms of the following characteristics: different areas of the world vary in importance to the United States; the probabilities of action occurring vary by area; and level of Naval air power required to effect a solution to any problem varies according to certain military, political, and economic considerations. Note that these are no longer technical trade-offs as a function of threat, but rather are social, political, and economic factors. This breakdown represents a partitioning of the high-level utility considerations into separate, meaningful components.

To assess the worth of NAWS forces in terms of the politico-military environment, two factors must be considered: the importance of the different areas of the world in which U.S. naval forces operate and the degree to which

NAWS contributes as an element of U.S. power in those areas.

The importance to the U.S. of a geographic area is sensitive to foreign policy changes, international economic changes, and the like. The contribution of NAWS in each area changes as the military strength and character of foreign forces change and as bases available for U.S. use are reduced in number. For these and other reasons, provision for using different area weights in five-year periods is made in the initial evaluation model.

Selected analytical data and forecasts can be used to develop relative area importance for the bounded regions shown in Figure 3-1. Data may be combined with expert forecasts to define current relative area importance and inter-area changes which can be predicted in the 20-year period of interest. The interactive computer graphic capability permits changes to be easily introduced and examined.

A method of quantifying the current importance of an area was developed by DDI analysts and used successfully in earlier work (see Footnote 2). This method was found to be highly appropriate to the development of this model and was subsequently used for inputs in testing the computer program of the final model. Four indicators of area importance were selected, quantified, and then summed to give equal weight to each indicator. The indicators and the sources of data are:

- Dollar value of economic and military assistance provided by the U.S. since 1945. Source: U.S. News and World Report, January 20, 1975
- Cost of U.S. General Purpose Forces associated with each area. Source: Setting National Priorities: The 1974 Budget, Brookings Institution.
- Dollar value of U.S. imports and exports. Source: Statistical Abstract of the United States, 1975.
- Multilateral and bilateral treaties and agreements of the U.S. Source: "Treaties in Force: 1975," U.S. Department of State.

With each of the foregoing indicators of importance, it is possible to apportion the data to areas in numerical form and then represent the numerical forms as percentages among areas. Because it is difficult to predict which of the five-year time periods may be more critical in world history, each column is normalized to sum to 100%. All of these elements are accommodated by and clearly displayed in the format shown in Table 4-6 below.

AREA	1976-80	1981-85	1986-90	1991-95
N. LANT				
W. PAC				
I. O.				
MED				
S. LANT				
E. PAC				
Sum	100%	100%	100%	100%

Table 4-6: Area Importance for Time Periods

The contribution of NAWS to deterrence within each area is developed next. A feasible method for estimating this contribution is to apportion the political, economic, and military means available to accomplish a U.S. objective within each area. The respective percentages of political, economic, and military influence are estimated by experts, area by area. Then the military means is broken down according to the percentage which is tactical air and finally the percentage of tactical air in each area which is NAWS. The results of these calculations are entered in the matrix shown in Table 4-7.

AREA	1976-80	1981-85	1986-90	1991-95
N. LANT				
W. PAC				
I. O.				
MED				
S. LANT				
E. PAC				
Sum	$\neq 100$	$\neq 100$	$\neq 100$	$\neq 100$

Table 4-7: Naval Aviation Weapon System Contribution in Area

The politico-military weighting factor for each area of the world in the specified five-year time periods is obtained by multiplying corresponding cells in the two matrices displayed in Tables 4-6 and 4-7 and then renormalizing each column to sum to 100. The figures are displayed in the format shown in Table 4-8.

AREA	1976-80	1981-85	1986-90	1991-95
N. LANT				
W. PAC				
I. O.				
MED				
S. LANT				
E. PAC				

Table 4-8: Relative Area Weight

These politico-military weighting factors essentially constitute a measure of the potential importance of areas of the world. It is also necessary to have some idea of the likely distribution of actual enemy forces, for the potential contribution of NAWS to a world area will not be very great if there is no enemy threat in the area.

4.2.3 - Area distribution of opposition forces - A NAWS force mix which represents a credible worldwide deterrent must be balanced against the potential opposition. Thus, the next factor considered in the evaluation model is the potential opposition general order of a battle, that is, the distribution and deployment of the forces which constitute the potential opposition. This order of battle, developed for the general deterrence scenario for each of the five year periods, is displayed in Table 4-9. Each matrix cell in the figure contains the percent of the type of threat indicated by the column heading for the area of the world designated by the row heading.

The next step is to break down each cell in Table 4-9 into the percentage of opposition capabilities in each threat level within an area. For example, assume that there are a total of 400 submarines in the North Atlantic and that they constitute 40% of the worldwide submarine threat total. Of these, suppose only two countries have predominantly nuclear submarine forces, each has 100 submarines in its North Atlantic force, each country has exhibited excellent operational doctrine, and each force could gravely damage U.S. sources in the North Atlantic. Thus, half of the North Atlantic submarines, or 20% of the world total, fits the definition of high threat. Similarly, it is assumed that 100 mostly non-nuclear submarines are distributed among several countries in the North Atlantic area. These submarines demonstrate average tactical prowess, and pose only moderate damage potential. Thus, one-fourth of the North Atlantic submarines (or 10% of the world total) fits the definition of medium threat. The remaining one-fourth of the North Atlantic submarines fits the definition of low threat. The same technique can be applied to the process of dividing the other categories of opposition by threat level.

1976-80	SUBMARINES	STRIKE AIR	AIR-AIR DEFENSE	SURFACE DEFENSE
N. LANT				
W. PAC				
I. O.				
MED				
S. LANT				
E. PAC				
Sum	100%	100%	100%	100%

Table 4-9: Opposition General Order of Battle

The next step is to link the potential opposition with the counter-mission or missions of U.S. NAWS forces. It is assumed for this model that missions can be directly related to opposing force capacities identified in the Table 4-9 format and broken down by threat as follows:

- Land-based ASW and sea-based ASW counter submarine opposition,
- Fleet air defense strike air counters opposition,
- Escort and strike support counters air-to-air opposition,

- o Day/Night visual attack counters surface defense, and

- o All-weather attack counters surface defense.

Then the four-column matrix represented in Table 4-9 is transformed into a six-column matrix, with mission headings for the columns, by using the above relationships. The resulting format is shown in Table 4-10.

1976-80							
AREA/THREAT \ MISSION		L-B ASW	S-B ASW	FAD	ESS	VIS ATK	A/W ATK
N. LANT	H						
	M						
	L						
W. PAC	H						
	M						
	L						
I. O.	H						
	M						
	L						
MED	H						
	M						
	L						
S. LANT	H						
	M						
	L						
E. PAC	H						
	M						
	L						
Sum		100%	100%	100%	100%	100%	100%

Table 4-10: Order of Battle Distribution by Mission

Expert forecasts are used to develop the matrices for the five-year periods in the 1981-95 time span, as shown in Table 4-10. Again the interactive computer graphic capability permits changes to be introduced and examined with relative ease.

The matrix illustrated in Table 4-10 distributes the potential opposition within a mission by area and threat level. The matrix illustrated in Table 4-8 provides a weighting for the importance of each area that contains relevant political, economic, and military aspects. Each row in the matrix in Table 4-10 is multiplied by the corresponding area weight from the matrix of Table 4-8. This computation results in a single matrix for each five-year period, which assigns weights to threat levels in areas where these weights are based on the military, political, and economic importance of an area to the U.S. as well as the likely opposition in the area. This matrix will be designated as the area threat importance matrix.

4.2.4 <u>The utility for deterrence</u> - The area threat importance matrices resulting from the analysis discussed in Section 4.2.3 contain numerical values stemming from politico-military considerations for deterrence. The values developed in the matrix displayed in Table 4-5 represent the relative utility of effectiveness for the reference systems in deterrence, which is conditioned by operational and technical system considerations. All considerations affecting utility have been consistently applied in developing these two sets of matrices. Combining them by multiplying cells in the area threat importance matrix rows by corresponding cells in the associated mission columns in the weighted relative mission importance matrix of Table 4-5 results in a matrix for each five-year period having the format in Table 4-11. This matrix is the utility of reference systems in deterrence.

Scenario 1		1976-80					
AREA/THREAT \ MISSION		L-B ASW	S-B ASW	FAD	ESS	VIS ATK	A/W ATK
N. LANT	H						
	M						
	L						
W. PAC	H						
	M						
	L						
I. O.	H						
	M						
	L						
MED	H						
	M						
	L						
S. LANT	H						
	M						
	L						
E. PAC	H						
	M						
	L						

Table 4-11: Weighted Utility of Reference Systems - Scenario 1 (deterrence)

4.3 Utility Assessments for Scenarios involving Conditions Other than Deterrence

Scenario 1, which specifies a status of deterrence in all areas, provides a baseline for judgments with respect to other situations. The fact that deterrence is actually taking place at all times means that the utility judgments derived for Scenario 1 are, in essence, minimal utilities for other scenarios. When situations other than deterrence occur in scenarios, the added utility of effectiveness in missions can be estimated and added to those for Scenario 1. Thus, Scenario 1 provides a point of reference against which to weigh judgments concerning area importance, utility of effectiveness, and so forth.

Scenarios 2 through 15 involve a situation other than deterrence (for example, Crisis, UMA, or War) in one and sometimes two or more areas of the world. A posture of deterrence will still be maintained in those areas unaffected by the specified non-deterrence condition and utilities, for those unaffected areas can be assumed to remain essentially unchanged. Since there is no change in those areas, it is possible to consider only the affected areas in making judgments about scenario conditions. In Scenarios 2 through 15, a representative real opponent in the area as well as the associated threat levels in missions and the relative increase in importance of the outcome to the U.S. because of the scenario conditions can be assumed. A negligible error is introduced when, for purposes of simplification, the utility matrices for a scenario are obtained by using the Scenario 1 matrix and modifying only the utilities for the areas affected by the scenario condition.

The procedure chosen for modification is the following. For any area of the world in which a non-deterrence condition occurs, the relative importance of that condition as compared to deterrence in that area is assessed. For example, a particular crisis may be assessed as twice as important as general deterrence in an area. Then each value for that area is increased by an amount equal to 200% of the deterrence value. That is, the increased value of the non-deterrence condition of an area is added to the value of deterrence because the non-deterrence condition will usually be restricted to a small section of the larger area and a posture of deterrence will still be maintained in all other parts of the area. The computer program thus does not allow for different readjustments of individual cells within an area because of a particular non-deterrence condition. Such a condition is allowed to change only the overall importance of the area. If this seemingly reasonable simplification proves to be unrealistic, the approach can be altered to allow individual readjustment of missions within areas.

As indicated in Table 4-12, the base matrix for Scenario I is normalized to sum to 1800. The sum of all values in the matrices for scenarios 2 through 15 does not sum to 1800 because of the added importance and associated utility for effectiveness for specific conditions in world areas. These assessments thus result in a total of 60 matrices (15 scenarios for four different time periods).

Scenario 1	1976-80					
MISSION / THREAT	L-B ASW	S-B ASW	FAD	ESS	VIS ATK	A/W ATK
H						
M						
L						
(Sum = 1800)						

Scenario 2	1976-80					
MISSION / THREAT	L-B ASW	S-B ASW	FAD	ESS	VIS ATK	A/W ATK
H						
M						
L						
(Sum ≠ 1800)						

Scenario 15	1976-80					
MISSION / THREAT	L-B ASW	S-B ASW	FAD	ESS	VIS ATK	A/W ATK
H						
M						
L						
(Sum ≠ 1800)						

Table 4-12: Utility Aggregated across Areas

4.4 Utilities Summed across Areas, Scenarios 1 through 15

All of the considerations which require analyses, area estimates, and area forecasts have been taken into account in the 60 weighted utility matrices obtained by the processes described. These numbers are, in essence, expected utilities since area probabilities have been taken into consideration by using the order of battle. Because the aircraft weapon system effectiveness will be given in missions dependent only upon threat level, it is desirable to have the utility of effectiveness in missions against threats aggregated across areas. This aggregated utility is obtained by simply summing the expected utilities across areas within threat to derive the desired utility matrix in the format shown in Table 4-12. This number is the expected utility of the effectiveness of the reference air systems in the missions against threats for each scenario.

4.5 Scenario Probability

As indicated, utilities are first calculated within scenarios and then aggregated across areas within threats to provide a 3-by-6 threat-by-mission utility matrix for each scenario. These matrices are then weighted by the associated scenario probabilities to yield a final 3-by-6 scenario-independent matrix.

The assignment of scenario probabilities is a significant element of this analysis. In theory, a scenario has an extremely low probability since the greater the detail of a specific scenario, the lower the probability of its co-occurrence. Yet the probabilities assigned to scenarios must sum to 1.0.

A possible approach to probability assessment is to have the expert assess the odds that one scenario will occur as opposed to another and, after all odds judgments are made, convert them to probabilities that are normalized to sum to 1.0. This procedure is appropriate only if the scenarios form an exhaustive representation of the future world. However, each scenario actually represents a (possibly broad) class of situations. The probability attached to the scenario should, therefore, be the probability of the class of situations of which the scenarios is representative. If the expert considers that class of situations in assessing the odds, there is no problem. However, if he considers the probability of the scenarios alone, he may ignore the problem of appropriately representing the entire space and thus incorrectly weight scenarios.

Since appropriately representing the entire scenario space and assigning probabilities to scenarios are not easy tasks, sensitivity analyses should be performed to ascertain the amount of allowable error in probability (or utility) estimation. Very often, large errors in estimation must occur before decisions will change. The purpose of the decomposition effort is, of course, to decrease the probability of large errors by asking for meaningful decomposed judgments. Perhaps the most difficult of these judgments is this assessment of scenario probabilities, for the reasons already explained.

In light of these considerations, the probability of occurrence of each scenario is elicited from experts for the five-year time periods and displayed in the format shown in Table 4-13.

Scenario	1976-80	1981-85	1986-90	1991-95
1				
2				
3				
4				
5				
6				
7				
8				
9				
10				
11				
12				
13				
14				
15				
Sum	1.0	1.0	1.0	1.0

Table 4-13: Scenario Probabilities

4.6 Aggregation of Utilities across Scenarios

The utility matrices displayed in Table 4-12 are next weighted by appropriate scenario probabilities from Table 4-13, and the weighted products are summed across scenarios within threats and missions to yield four resulting utility matrices (one for each time period) which are thus scenario-independent matrices that contain the expected utilities of reference systems in missions against threats. These are illustrated in Table 4-14.

1976-80						
THREAT \ MISSION	L-B ASW	S-B ASW	FAD	ESS	VIS ATK	A/W ATK
H						
M						
L						

1981-85						
THREAT \ MISSION	L-B ASW	S-B ASW	FAD	ESS	VIS ATK	A/W ATK
H						
M						
L						

1986-90						
THREAT \ MISSION	L-B ASW	S-B ASW	FAD	ESS	VIS ATK	A/W ATK
H						
M						
L						

1991-95						
THREAT \ MISSION	L-B ASW	S-B ASW	FAD	ESS	VIS ATK	A/W ATK
H						
M						
L						

Table 4-14: Weighted Utility for Reference Systems

4.7 Calculating the Utility of Force Mixes

Sections 4-1 through 4-6 describe the steps in developing a multi-attribute utility model for the utility of the reference systems as they are defined in the overview of the methodology in Section 2.2. In this section, these "reference" utilities will be used to calculate the utility of existing and candidate NAWS and the utility of naval air forces containing those systems in alternative force mixes.

4.7.1 Assumptions used in assessing utilities of mixes - Since the mission effectivness of an existing candidate system is expressed as a precentage of the mission effectiveness of the reference system associated therewith, the utility of that system can be expressed as that same percentage of the utility of the reference system. It is assumed in the initial evaluation model that the product obtained is the utility of a single unit in the inventory and that multiplying that product by the number of units in a particular mix gives the net utility of that system in the mix.

This approach is valid if the total class inventory is reasonably close the inventory objective for the class. Large inventory changes cannot rationally be expected to provide linear changes in utility. Fortunately, large changes are unlikely because the viable alternatives of the NAP will specify total class inventories close to the inventory objective.

However, some very important assumptions are involved here. One assumption is that the utility for numbers of the same system is linear with the numbers. This assumption is illustrated in Table 4-15 for the VAL class. As indicated,

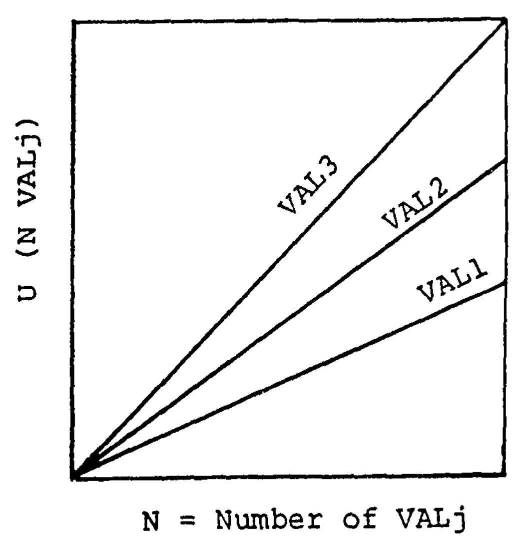

Table 4-15: Utility of Numbers of VALj

this assumption seems reasonable if class inventories remain close to inventory objectives. If not, the model can be refined by degrading the utility of systems as the numbers of such systems depart from ideal levels of inventories. This refinement can be accomplished by calculating the system utility as a function both of the system effectiveness and of the number of that class of systems in the mix.

Table 4-16 illustrates another assumption, namely, that the utility trade-offs between NAWS of different classes are independent of the numbers involved. The trade-off illustrated is for the VF and VAL classes.

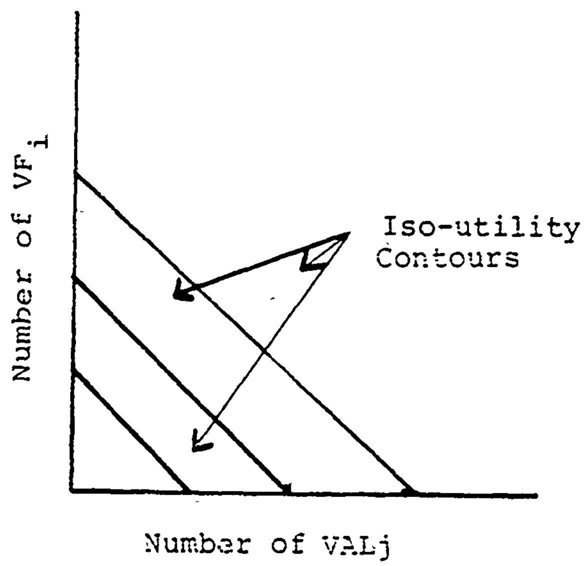

Table 4-16: Utility Trade-offs for Different Numbers of VF_i versus VAL_j

This assumption states that the utility for different numbers of one class of system in a mix is independent of the numbers of other classes of systems.

This utility independence condition for numbers of systems can be illustrated with the following hypothetical example: If in a particular mix there are 100 VF-A's and 100 VAL-B's, and for a high threat, the utility of the effectiveness of a VF-A is considered to be twice the utility of the effectiveness of a VAL-B, then the same ratio of effectiveness is true if the mix consists of 80 VF-A's and 120 VAL-B's. Stated in this manner, the potential for violation of the condition should be evident. However, the manner in which systems are employed lessens the probability of such a violation. Systems are generally deployed to yield whatever weight of capability is necessary for the missions they may be called upon to perform. Carrier airwings are composed to yield the necessary total effectiveness in missions, and if a certain additional aircraft type with its associated effectiveness is needed, the aircraft can usually be flown aboard the carrier. Thus, the real problem would occur only if a mix did not at all contain the required balance of mission capability. This condition is not likely, for the Navy, in developing viable force mixes, necessarily attempts to maintain balanced force effectiveness to be able to perform effectively all naval air missions.

Still, it could be the case that the assumption concerning utility trade-offs and numbers is an inaccurate one. If so, the utility of the effectiveness of one class of systems can be assessed conditional upon varying levels of support from the class upon which the utility is dependent. The model can be expanded to incorporate these conditional utilities. Again, the number of dependencies is small enough to make this procedure a reasonable solution.

4.7.2 Procedures for combining individual system utilities in assessing force mixes - The following sections describe that part of the evaluation model which provides the planner with decision-aiding assessments of alternative plans.

Each system has a unit utility equal to the product of its relative effectiveness in a mission and the corresponding utility for its reference system. The required inputs for the calculation are utility of reference systems (Table 4-14) against threats, system effectiveness relative to reference system, and mission multiplier (for multiple mission systems, see below).

As discussed, the utility of reference systems has been developed by using the evaluation model. Relative system effectiveness is provided from Navy technical sources. However, a problem occurs for multi-mission systems. What weights should be assigned the utilities of effectiveness of such systems in the different missions? Clearly, simple addition of utilities would assign far too much utility to multiple-mission air systems. At the same time, multiple-mission capability should enhance the utility of the air system.

One approach is to weight each mission by the probability that the air system will be involved in that mission. This approach is not acceptable because no utility is added for multi-mission capability. Moreover, the systems will very likely be used in missions in proportions directly related to the importances of the missions. Thus, a second weighting of missions could be based upon the average importance associated with the missions. Another way of incorporating additional utility for multi-mission capability would be to add a proportion, say 5%, to the system utility in its primary mission, which accounts for the multi-mission capability. Given the different possible interpretations of mission weight, the approach outlined in this report leaves the multiple-mission weight assignment to the Navy technical sources. The advantage to this approach is that it places responsibility for such judgments with the proper technical experts.

A mission multiplier is thus used in the model to account for the fact that some NAWS are designed with multi-mission capability. The model uses a weighted sum, with a factor for the design primary mission, a factor for secondary mission, and so forth. These factors are multipliers which sum to a total equal to or greater than one preserving relationships and accounting for the multi-mission additional benefit. These factors, expressed in symbols are:

M_p = primary mission multiplier,

M_s = secondary mission multiplier,

M_t = tertiary mission multiplier, and

$1.0 \leq M_p + M_s + M_t \leq 3.0$

The initial evaluation model has provisions for handling system capability in one, two, or three missions. Multiple-mission capability is then handled with the mission multipliers in a manner based on the following rule:

Single Mission	Double Mission	Triple Mission
$M_p = 1.0$	$1.0 \leq M_p + M_s \leq 2.0$	$1.0 \leq M_p + M_s + M_t \leq 3.0$
$M_s = M_t = 0$	$M_t = 0$	

As indicated, the multiplier is not calculated in the model; it is provided from Navy technical sources along with the relative system effectiveness inputs. The utility of a single unit of each system is calculated in the following steps:

- Multiply system effectiveness by reference system utility (Table 4-14) to obtain the utility of each system in mission and threat by year;

- Multiply system utility by the corresponding mission multiplier to obtain the weighted utility of each system in mission and threat by year; and

- Sum the weighted utility across missions and threats in each year to obtain the utility of a single inventory system.

Note that the calculation of the utility of individual systems by simply adding utilities for the systems across threats is possible because these utilities are expected utilities that already have taken threat probability and importance into account. The resulting utility of one inventory unit of each naval aircraft weapon system under consideration is then displayed as shown in Table 4-17.

SYSTEM UTILITY - SINGLE UNIT																	
YEAR \ SYSTEM	A	B	C	D	..	L	M	N	..	U	V	W	..	AA	AB	..	AH
1976																	
1977																	
1978																	
1979																	
1980																	
1981																	
1982																	
1983																	
1984																	
1985																	
1986																	
1987																	
1988																	
1989																	
1990																	
1991																	
1992																	
1993																	
1994																	
1995																	

Table 4-17: Unit System Utility

The unit utility of each system in each year is available from the calculations described in Sections 4.1 through 4.6 and is shown in Table 4-17 above. The inventory numbers for each system are established by the Navy in the process of developing the viable alternatives for the NAP. Multiplying the unit utility for each system by the corresponding number in inventory gives the net system utility for each of the postulated mixes. A display format for net utilities associated with one mix is shown in Figure 4-18.

A convenient display of the total utility for each of the postulated mixes is obtained by tabulating the sum of each column in Table 4-18. The resulting display is shown in Table 4-19.

Although this illustration shows six mixes, the model is not limited to this number. Additional mixes, limited in number only by computer capacity, may be evaluated, and variants of each mix can be assessed by making selective inventory changes within a postulated force mix.

An interactive graphic capability permits the selection of rows or columns in most of the displays for graphic presentation and comparison and may be designed for sensitivity analyses, as shown in Table 4-19.

Mix ____	NET SYSTEM UTILITY																			
	1976	1977	1978	1979	1980	1981	1982	1983	1984	1985	1986	1987	1988	1989	1990	1991	1992	1993	1994	1995
Class																				
A B C :																				
Class																				
L M N :																				
Class																				
U V W :																				
Class																				
AA AB AC :																				
TOTAL																				

Table 4-18: Net Utility of Systems in the Force Mixes

Year	UTILITY					
	Mix 1	Mix 2	Mix 3	Mix 4	Mix 5	Mix 6
1976						
1977						
1978						
1979						
1980						
1981						
1982						
1983						
1984						
1985						
1986						
1987						
1988						
1989						
1990						
1991						
1992						
1993						
1994						
1995						
Total						

Table 4-19: Net Expected Utility of Each Mix

5.0 RESULTS AND CONCLUSIONS

5.1 Results

A utility model which provided a method for calculating the expected utility of NAWS and evaluating alternative force mixes was developed. A means was provided to make evaluations across classes of aircraft for the NAP.

The evaluation model has been programmed on an interactive computer graphic facility and demonstrated successfully by using an abbreviated group of aircraft systems and four representative inventory mixes of those systems. The test data are shown in Appendix A of this report. Figure 5-1 below shows the test results for the four hypothetical force mixes. The net expected utility in FY 1976 is the same for all force mixes because the starting point for all alternatives will be the actual inventory in the current year, in this example, Fiscal Year 1976. However, decision options which will change the force mix were selected to test the model[1] and altered the net expected utility for the alternative force mixes in later years as shown.

The test of the utility model with representative numbers showed that it differentiates among mixes and that expected utility values change in the proper direction as inventory and capability inputs are varied. A perception of scale is lacking in the numbers of Figure 5-1 inasmuch as a reference point such as the maximum mix utility was not calculated. The calibration of the model by using inputs from responsible sources will make expected utility numbers meaningful to the analyst and decision makers.

The model also facilitates tracking the utility of specific systems over time. Table 5-1 below shows the net utility summed for the NAWS in each of the four classes of systems used in Mix 1 of the numerical test. This breakdown illustrates the value of the analyst's being able to track within the NAP the elements which are static, improving, or degrading over time. In the above example, System Class II

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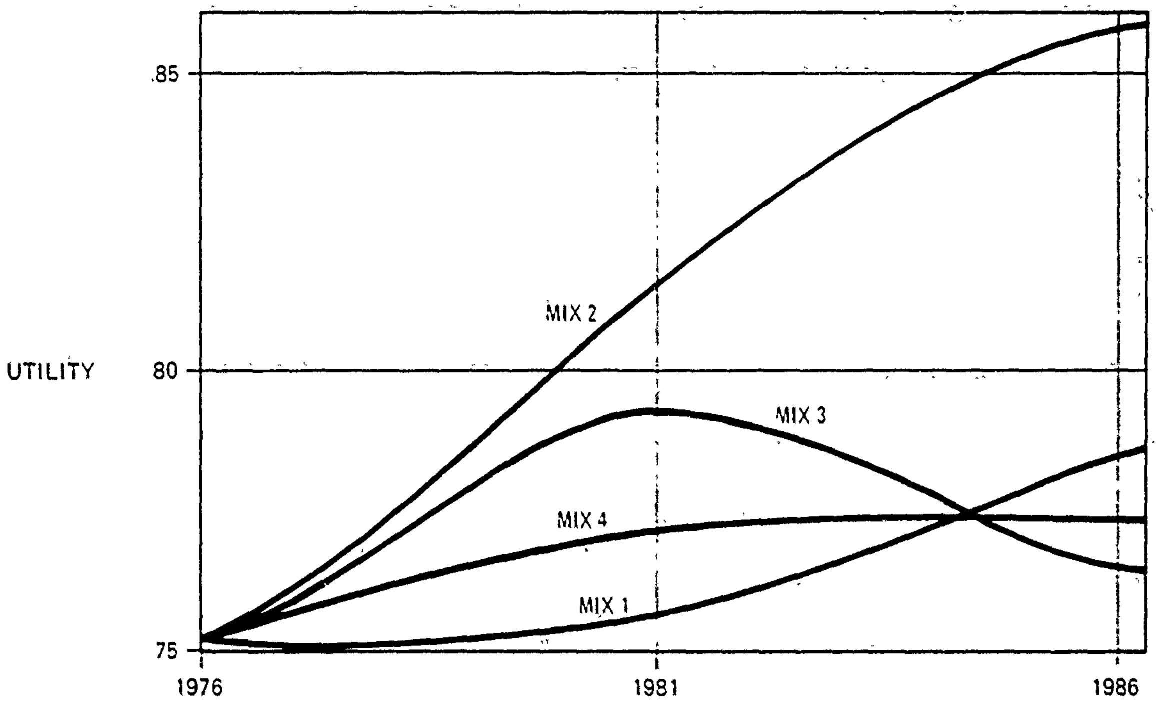
[1] Mix 1 assumes an orderly introduction of new low-mix systems, a final inventory build-up following a mid-term inventory shortfall and slight program cost increases. Mix 2 assumes the acquisition of high-mix systems and a continuous inventory build-up requiring substantial program cost increases. Mixes 3 and 4 are variants of Mix 1, in which the introduction of new systems is delayed on a selective basis and the inventory shortfall is not as severe.



MIX	DESCRIPTION	COST
1	INVENTORY DIP WHILE "LOW MIX" SYSTEMS ACQUIRED	LOWEST
2	MAINTAIN INVENTORY AND ACQUIRE "HIGH MIX" SYSTEMS	HIGHEST
3	MAINTAIN INVENTORY AND ACQUIRE SOME OF BOTH	MEDIUM
4	MAINTAIN INVENTORY BUT PRODUCE CURRENT SYSTEMS LONGER	LOW

Figure 5-1: **NET EXPECTED UTILITY FOR FOUR HYPOTHETICAL MIXES**

MIX 1

Net Utility by Class

SYSTEM CLASS	1976	1981	1986
I	24904	25180	27612
II	26283	26425	22927
III	14286	14154	17868
IV	9706	9977	10023
TOTAL	75179	75736	78430

Table 5-1: Net Utility for Four Aircraft Weapons Systems in the Mix Evaluated in Figure 5-1

is significantly degraded by the year 1986, while Classes I, III and IV are upgraded, and the overall utility of Mix 1 is increasing with time.

The analyst is able to quickly call up more detailed displays which show utility, effectiveness, and inventory numbers for Mix 1 and the Class II systems therein. With these information inputs he can complete his understanding of Mix 1 as an alternative for the NAP and proceed with his assessment and comparison of the remaining mixes. Pinpointing the reason is possible.

One of the major objectives of the project was to develop a model which could be used for inter-class comparisons between NAWS. Intra-class trade-offs are in general facilitated because dimensions of utility and effectiveness are common within like missions for all systems in a class. Global judgments within like missions, though difficult, are defensible. On the other hand, inter-class trade-offs, requiring comparison across different missions and therefore different effectiveness criteria, are complicated by the expectation that all missions must be performed and by the fact that missions are often inter-dependent.

The solution was to decompose the very difficult problem of quantifying inter-mission global judgments into the manageable problem of quantifying less global judgments. Such component judgments can be aggregated into valid inter-class system utilities.

5.2 Conclusions

This utility model has some practical benefits which derive from the methodology and the interactive computer graphic capability. First, alternative force mixes can be evaluated quickly and economically. Second, because the results are traceable through the model, the reasons why each force mix scores as it does in relation to the others can be studied. Third, new combinations of inventory and effectiveness levels for NAWS can be easily inserted into the computer for quick assessment of alternatives or for sensitivity analysis. Similarly, sensitivity analyses of the effect of dynamic changes in political, military, and economic factors considered in the model can be made.

The potential uses as well as the techniques for exploiting the capabilities of the evaluation model have been only minimally explored. However, it is already evident that the model is a flexible analytical decision aid. The following examples illustrate the range of problems which can be considered:

- Given a number of combinations of future candidate systems and inventory projections, determine the expected utility of viable alternatives for the NAP;

- Given the options for improvement in individual system effectiveness from developing technology, determine the effect of technology program choices on the expected utility of the force; and

- Given the uncertainties in future political-military situations in the major maritime regions, determine the expected utility of viable naval air force structures for a suitable range of projections of world conditions.

The value of any analysis is based upon its recognized validity, degree of applicability, and measurable benefit. The analysis presented in this work should be examined in light of these criteria.

The validity of the model rests on both the quality of input judgments and the validity of the many independence assumptions made. One element of validity involves the subjectivity of certain judgments used in the analysis. The methodology outlined in this report admits subjective inputs when necessary. The inter-class trade-offs, importance of threats, construction of scenarios and associated probability assessments, mission multipliers, and so forth require human judgments and are therefore susceptible to error. Sensitivity analyses identify the areas in which such errors are crucial and which, therefore, require concentrated attention. Nevertheless, it is possible that more complex modeling of certain aspects of the task could have been accomplished. The question is, what gain would have been derived from the added effort and expense? No doubt, the independence assumptions are occasionally violated, but since the output of any evaluation model is an approximation of the actual value of the system, a small number of violations do not ordinarily render the approximation invalid. In this case, sensitivity analysis does not invalidate any approximations based on such assumptions. And, as discussed, the model can be expanded to accommodate more complex dependencies when necessary.

The second criterion, applicability, is perhaps more significant than validity since many completely valid models are never or rarely used; they are either too large or too expensive to implement. Furthermore, many approaches involve complex simulations, the assumptions and model structures of which are not traceable. Thus, even when implemented, the output is often accepted reluctantly, if at all.

The model herein described, although highly detailed, is a straightforward one; the assumptions are clear and testable, and the inputs have been subject to evaluation by using the interactive graphic capability employed in the computerization. The main point is that the structure is open to challenge, and if such challenge uncovers problems, the model is subject to modification. The public nature of the model reveals to the decision maker exactly how his decision problem is being decomposed into components. This explicitness lends a credibility that large complex simulations often do not afford.

Finally, the benefit derived from any analysis is a direct measure of its worth and effectiveness. The model, if valid, facilitates accurate evaluation of the NAP. This model is a utility model in the sense that only questions concerning the utility of capability are involved. Technical capabilities of NAWS are taken as input. These measures can be the result of simulations or other procedures. But, as earlier indicated, eventually the question of the relative worths of different kinds of capability must be predicted, and prediction is an inherently judgmental task. The model developed for this analysis organizes that judgmental effort.

APPENDIX A

NUMERICAL TEST

A.1 Inputs for Calculating the Weighted Utility for Reference Systems

A test of the model was run after it was programmed on the computer. In the sections which follow, the sets of hypothetical numbers which were used as inputs to the computer are shown, with one exception. The final matrix of numbers shown is a calculated matrix, the weighted utility for reference systems, which was obtained through combination of the input matrices as described by the model.

A.1.1 Relative Mission Importance vs. Threat

THREAT	L-B ASW	S-B AWS	FAD	ESS	DAY ATK	N-AW ATK
HIGH	90	100	100	90	95	85
MEDIUM	65	80	95	55	100	90
LOW	60	90	90	55	100	90

A.1.2 Relative Importance of Countering Threat

THREAT	
HIGH	100
MEDIUM	90
LOW	70

A.1.3 Area Importance vs. Time Period

AREA	1976-80	1981-85	1985-90	1991-95
N. LANT	37	37	36	36
W. PAC	24	22	21	21
I. O.	8	9	10	10
MED	15	16	17	17
S. LANT	6	6	7	8
E. PAC	10	10	9	8

A.1.4 Naval Aviation Contribution in Area

AREA	1976-80	1981-85	1986-90	1991-95
N. LANT	6	6	8	10
W. PAC	37	40	42	45
I. O.	58	60	63	65
MED	22	25	26	28
S. LANT	7	7	9	10
E. PAC	2	2	2	2

A.1.5 Opposition General Order of Battle 76-80

NOTE: For this test, the same percentages were used for succeeding periods.

AREA	SUBMARINES	STRIKE AIR	AIR-AIR DEF	SURFACE DEF
N. LANT	40	34	32	30
W. PAC	32	28	22	25
I. O.	1	1	5	5
MED	25	35	31	30
S. LANT	1	1	5	5
E. PAC	1	1	5	5

A.1.6 Opposition Threat Distribution (76-80)

AREA	THREAT	SUBMARINE	STRIKE AIR	DEFENSES
N. LANT	H	.70	.50	.60
	M	.25	.40	.35
	L	.05	.10	.05
W. PAC	H	.40	.35	.30
	M	.50	.45	.45
	L	.10	.20	.25
I. O.	H	.10	.05	.05
	M	.20	.05	.10
	L	.70	.90	.85
MED	H	.55	.45	.40
	M	.35	.45	.50
	L	.10	.10	.10
S. LANT	H	.05	.05	0.00
	M	.15	.10	.10
	L	.80	.85	.90
E. PAC	H	.05	.05	0.00
	M	.15	.10	.10
	L	.80	.85	.90

NOTE: For this test, the same decimal distributions in each area were used for succeeding periods to partition the general order of battle.

A.1.7 Weight Factors for Scenario Importance

NOTE: Weight factors for Scenarios 2 through 15 are shown only when they are different from 1.

Scenario 2

AREA	THREAT	L-B ASW	S-B ASW	FAD	ESS	DAY ATK	N-AW ATK
MED.	M			10	10	10	10
	L	10	10				

Scenario 3

AREA	THREAT	L-B ASW	S-B ASW	FAD	ESS	DAY ATK	N-AW ATK
W. PAC	M				4	4	4
	L	4	4	4			

Scenario 4

AREA	THREAT	L-B ASW	S-B ASW	FAD	ESS	DAY ATK	N-AW ATK
I.O.	L	10	10	10	10	10	10

Scenario 5

AREA	THREAT	L-B ASW	S-B ASW	FAD	ESS	DAY ATK	N-AW ATK
N.LANT	M	4	4	4	4	4	4

Scenario 6 and Scenario 7

AREA	THREAT	L-B ASW	S-B ASW	FAD	ESS	DAY ATK	N-AW ATK
I.O.	L	10	10	10	10	10	10
MED	M			30	30	30	30
	L	30	30				

Scenario 8

AREA	THREAT	L-B ASW	S-B ASW	FAD	ESS	DAY ATK	N-AW ATK
MED	M			30	30	30	30
	L	30	30				

Scenario 9

AREA	THREAT	L-B ASW	S-B ASW	FAD	ESS	DAY ATK	N-AW ATK
N.LANT	H	80	80	80	80	80	80
W.PAC	H	10	10	10			
	M				10	10	10
MED	H	50	50	50	50	50	50

Scenario 10

AREA	THREAT	L-B ASW	S-B ASW	FAD	ESS	DAY ATK	N-AW ATK
W.PAC	M				10	10	10
	L	10	10	10			

Scenario 11

AREA	THREAT	L-B ASW	S-B ASW	FAD	ESS	DAY ATK	N-AW ATK
W.PAC	M				6	6	6
	L	6	6	6			

Scenario 12

AREA	THREAT	L-B ASW	S-B ASW	FAD	ESS	DAY ATK	N-AW ATK
I.O.	L	10	10	10	10	10	10
MED	M			10	10	10	10
	L	10	10				

Scenario 13

AREA	THREAT	L-B ASW	S-B ASW	FAD	ESS	DAY ATK	N-AW ATK
N.LANT	M	4	4	4	4	4	4
MED	M			10	10	10	10
	L	10	10				
S.LANT	L	50	50	50	50	50	50

Scenario 14

AREA	THREAT	L-B ASW	S-B ASW	FAD	ESS	DAY ATK	N-AW ATK
E.PAC	L	50	50	50	50	50	50

Scenario 15

AREA	THREAT	L-B ASW	S-B ASW	FAD	ESS	DAY ATK	N-AW ATK
I.O.	L	10	10	10	10	10	10

A.1.8 Scenario Likelihood Ratio

SCENARIO	1976-80	1981-85	1986-90	1991-95
1	50.34	48.63	47.02	47.02
2	37.75	31.61	28.00	0.0
3	5.03	9.73	14.10	14.10
4	2.52	3.40	4.70	4.70
5	1.01	1.95	2.35	2.35
6	1.01	1.46	.94	.94
7	.50	.97	.71	.71
8	.50	.97	.71	.71
9	.50	.49	.47	.47
10	.50	.49	.47	.47
11	.25	.24	.24	.24
12	.03	.03	.03	.03
13	.03	.02	.02	.02
14	.02	.02	.02	.02
15	.01	.01	.01	.01

A.1.9 Weighted Utility for Reference Systems (76-80)

THREAT	L-B ASW	S-B ASW	FAD	ESS	DAY ATK	N-AW ATK
HIGH	.193	.214	.170	.125	.134	.120
MEDIUM	.107	.132	.324	.184	.338	.305
LOW	.034	.050	.051	.034	.065	.059

NOTE: Matrices for (81-85) and (86-90) were also calculated in the test run and used with the system effectiveness percentages and inventory mixes for the years 1976, 1981, and 1986, which are shown in Section A.2 below.

A.2 System Effectiveness and Inventory Inputs

A.2.1 Percent Effectiveness Relative to Reference System

SYSTEM	1976 H	1976 M	1976 L	1981 H	1981 M	1981 L	1986 H	1986 M	1986 L
A	100	100	100	95	100	100	90	96	98
B									
C	40	65	90						
M D	40	64	90	35	60	90			
=.5 E	45	70	92	40	65	92			
F				45	70	92	40	65	90
G				60	80	100	50	70	90
H				55	75	95	45	65	85
A	100	100	100	100	100	100	94	100	100
B							94	100	100
C	55	80	90						
M D	55	80	90	50	75	90			
=.5 E	55	85	95	50	85	95			
F				55	85	95	55	80	90
G				85	100	100	75	95	100
H				80	95	100	70	90	100
L	100	100	100	85	100	100	70	95	100
M							70	95	100
N	80	90	95	60	80	90			
O				60	80	90	50	75	85
P	60	90	95						
Q							90	100	100
U	100	100	100	95	100	100	85	95	100
V	100	100	100	95	100	100	85	95	100
W	70	85	90	60	75	80			
X							92	98	100
Y							95	100	100
AA	100	100	100	98	100	100	95	99	100
AB	40	50	70	35	45	65			
AC	65	80	90	62	76	86	48	60	70
AD	70	83	92	67	80	90	72	88	98
AE				100	100	100	95	100	100
AF				95	100	100	85	95	100
AG				57	74	85	48	60	70
AH				61	78	89	53	67	79

A.2.2 Number in Inventory

SYSTEM	MIX 1 YEAR 1976	MIX 1 YEAR 1981	MIX 1 YEAR 1986	MIX 2 YEAR 1976	MIX 2 YEAR 1981	MIX 2 YEAR 1986	MIX 3 YEAR 1976	MIX 3 YEAR 1981	MIX 3 YEAR 1986	MIX 4 YEAR 1976	MIX 4 YEAR 1981	MIX 4 YEAR 1986
A	190	312	311	190	364	543	190	312	311	190	312	311
B			27			25			27			27
C	29			29			29			29		
D	179	85		179	88		179	85		179	85	
E	347	48		347	48		347	48		347	48	
F		217	207		217	207		217	207		217	207
G		15	339								15	339
H								58	226			
L	310	389	175	310	428	334	310	428	334	310	389	175
M			170			170			170			170
N	173	122		173	122		173	122		173	122	
O		7	81		7	81		7	81		7	81
P	32			32			32			32		
Q			65									65
U	73	81	71	73	121	112	73	81	71	73	114	105
V	154	196	172	154	196	172	154	196	172	154	196	172
W	84	12		84	12		84	12		84	12	
X						147						38
Y			147						38			
AA	110	140	140	110	70	70	110	140	140	110	70	70
AB	50	10		50	10		50	10		50	10	
AC	100	90	70	100	45	35	100	90	70	100	45	35
AD	110	110	100	110	55	50	110	110	100	110	55	50
AE		20	60		20	60		20	60		20	60
AF					70	70					70	70
AG					45	35					45	35
AH					55	50					55	50

A.3. Calculated Test Results

A.3.1 Net Effective Value of Mix 1

SYSTEM	1976	1981	1986
A	8434	14067	12942
B	0	0	1124
C	827	0	0
D	5107	2326	0
E	10536	1427	0
F	0	6793	5799
G	0	567	7747
H	0	0	0
L	16661	20925	8370
M	0	0	8131
N	8192	5202	0
O	0	298	3034
P	1430	0	0
Q	0	0	3392
U	3526	4012	3180
V	7438	9709	7705
W	3322	433	0
X	0	0	0
Y	0	0	6983
AA	3711	4517	4363
AB	772	135	0
AC	2416	2029	1218
AD	2807	2644	2566
AE	0	652	1876
AF	0	0	0
AG	0	0	0
AH	0	0	0
TOTAL	75180	75740	78428

NOTE: Net Effective Values for Mixes 2, 3, and 4 were calculated, and the totals are included in the final test output matrix below.

A.3.2 Net Expected Utility of Each Mix

	1976	1981	1986
MIX 1	75180	75740	78428
MIX 2	75180	81511	85684
MIX 3	75180	79339	76569
MIX 4	75180	77208	77502

APPENDIX B

GENERALIZED MATRIX MANIPULATION SYSTEM

B.1 Introduction

The Generalized Matrix Manipulation System was developed to facilitate the implementation of multivariate analysis models on the DDI Interactive Computer Graphics System. The Generalized Matrix Manipulation System provides a tool for displaying, modifying, and combining matrices according to a set of pre-specified values. The basic design concepts underlying the system will be discussed in order to introduce the user to the use of this modeling tool. Table B1-1 shows a functional block diagram of the system:

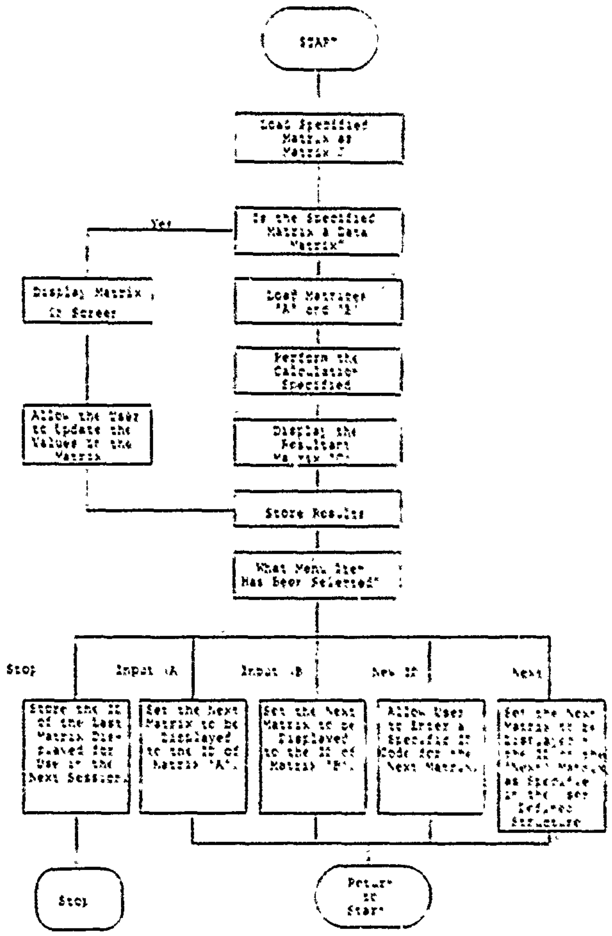


Table B1-1

So that the system can be used with models having matrices of significant size, a maximum of three matrices are resident in central memory at any point in time. There are two operand matrices (referred to as 'A' and 'B') and one result matrix (referred to as 'C'). The remaining matrices for the model reside on discs and are loaded into central memory as required. Table B1-2 provides general size constraints of models.

CURRENT LIMITATIONS

The following limitations are imposed by the program. Additional memory capacity is available to expand these limits if necessary.

Number of matrices in the model	- 600
Combined number of elements in resultant matrix and input matrices (number of elements in matrices A, B, and C combined)	- 1000
Number of characters in title	- 40
Number of characters used for row labels and column labels combined	- 500
Maximum number of elements in vector INDEX	- 50

Table B1-2

Matrices A and B are not used for those matrices that contain initial data values; the initial data values are loaded directly from disc into Matrix C. These matrices are referred to as type 1 or data matrices.

Type 2 or calculated matrices are generated by using a set of predefined rules. These rules are referred to by number (see B.2 when the model is coded for input into the system and can be generally thought of as "Matrix C is developed by combining Matrix A with Matrix B as specified in Rule N").

After Matrix C has been calculated (or loaded, as in the case of data matrices), it is displayed on the screen by using column and row labels specified in the model. At this point, individual items in data matrices can be edited by selecting them with the light pen and typing in new values.

After the user has examined the matrix being displayed, he may select one of five options:

STOP — Terminate current session (may be continued at some later point in time);

INPUT (A) — Have the operand matrix 'A' loaded into central memory and displayed;

INPUT (B) — Have the operand matrix 'B' loaded into central memory and displayed;

NEW ID — Request the user to type the identification code of the next matrix to be displayed; or

NEXT — Have the next matrix as defined in the model structure loaded and displayed.

The user may continue in this manner until value changes are propagated throughout the model only when the user steps forward through the logic of the model using the NEXT option (or the NEW ID option). If the user jumps back in the model to modify values in some matrix by selecting INPUT (A), INPUT (B), or NEW ID, he must step forward through the appropriate branches of the model logic until he reaches his original point.

Section B.3, Data File Structure provides the user with the necessary data formats and further explanation of individual data elements and their use.

Section B.4, Example Model, is a simplified example which carries a problem from structuring through coding to execution.

B.2 Matrix Combining Rules

Rule Number	Operation
1	Element-by-element multiplication of Matrix A by Matrix B with the result in Matrix C.
2	Element-by-element multiplication of A by B where A is N times as many rows as B. The elements in row 1 of B are multiplied by the corresponding elements of rows 1, 2,...N of A, the N row 2 of B is multiplied by rows N+1, N+2....N+N of Matrix A, etc.
3	The columns in Matrix A are multiplied by the column vector B and stored in the upper left-hand corner of Matrix C.
4	Element-by-element multiplication of A by B with relative column addresses taken from the vector INDEX. (Columns of A are multiplied sequentially by columns of B in the order specified in vector INDEX.)
5	Each row of A is multiplied by a row of B as specified in vector INDEX. The number of elements in vector INDEX must be equal to the number of rows in Matrix C.
6	Append Matrix B to the bottom of Matrix A to form Matrix C.
7	Append Matrix B to the right side of Matrix A to form Matrix C.
8	Copy Matrix A to Matrix C and set the edit switch for Matrix C so that it can be modified as if it were data.
9	The first N rows of Matrix A are summed to form row one of Matrix C, the second N rows of A are summed to form row two of Matrix C, etc. Therefore, C must have at least 1/Nth the number of rows as A.

Rule Number	Operation
10	Add the elements of Matrix A to the elements of Matrix B to form Matrix C.
11	Transpose Matrix A to form Matrix C (the rows of Matrix A become the columns of Matrix C).
12	Move Matrix A to Matrix C (put the upper left-hand corner of A in the upper left-hand corner of C. If A is bigger than C, the remainder is discarded. If A is smaller than C, excess elements will be zero.)
13	Move the Nth column of Matrix A into column vector C.
14	When Matrix A differs from Matrix B by a constant multiplier, determine the multiplier by dividing the value in element A(1,1) by the value in B (1,1). The result is stored in element C(1,1).
15	Form Matrix C by multiplying each element in Matrix A by a constant. The constant used is the value stored in element B(1,1).
16	Form Matrix C by extracting rows from Matrix A as specified in vector INDEX. The number of elements in vector INDEX must be equal to the number of rows in Matrix C.
17	Matrix C is formed by overlaying selected rows of Matrix B. The vector INDEX specifies which rows of A are replaced by the rows of B. The number of elements in INDEX must be equal to the number of rows in Matrix B.
18	Multiply each element in Matrix A by a single value stored in B(K,L), where K and L are the first two values in the vector INDEX K = INDEX (1) L = INDEX (2) C(I,J) = A(I,J) x B(K,L) There are two values stored in the vector INDEX.

B.3 Data File Structure

A model is specified to the Generalized Matrix Manipulation System by means of entries in a disc file called the Initialization Data File. The Initialization Data File can be created with the Vector General EDIT D text editor and is divided into two sections. The first section defines the column and row heading literals to be used for displaying specific matrices. The second section specifies a title and a definition for each matrix in the model.

The first section of the Initialization Data File must be formated as shown in Table B3-1 below:

	Values	Format	Information
	NLS	I10	Number of Label sets.
Label Set 1	NL(1), LEN(1)	2I10	Number of labels in set. Length of longest label plus one.
	LABEL(1)	80A1	
	LABEL(2)	80A1	
	-	-	
	-	-	
	-	-	
	LABEL(NL(1))	80A1	
Label Set 2	NL(2), LEN(2)		
	LABEL(1)		
	LABEL(2)		
	-		
	-		
	-		
	LABEL(NL(2))		
Label Set NLS	NL(NLS), LEN(NLS)		
	LABEL(1)		
	LABEL(2)		
	-		
	-		
	-		
	LABEL(NL(NLS))		

Table B3-1

The second section of the Initialization Data File contains three types of entries: Input Data Matrices, Computational Matrices, and Computational Matrices with special Indices (for computational rules 4, 5, 16, 17 and 18). The following format specifications should be used for preparing matrix definition records.

MATRIX DEFINITION RECORD STRUCTURE

Line	Variables	Definition	Format	Conditions
1	MATID	Six digit (or less) matrix identification code.	F10.1, 40A1, I1	Always include
	TITLE	40 (maximum) character title to be used displaying the matrix.		
	NP	Variable which controls whether or not matrix should be displayed. A value of zero causes the display while a value of one inhibits it.		
2	NROW	Number of rows in matrix.	8I10	Always include
	NCOL	Number of columns in matrix.		
	TYPE	1 - if a data matrix. 2 - if a calculated matrix.		
	METH	Method of calculation to perform (refer to matrix combining rules).		
	SUM	0 - no summation is to be performed 1 - the last column is to contain the sum of the elements in each row. 2 - the last row is to contain the sum of the elements in each column. 3 - both row and column sums should be calculated.		
	COLLAB	The index of the label set to be used for column headings.		
	ROWLAB	The index of the label set to be used for row headings.		
	NT	Control variable used in rules 2, 9, and 13 (refer to combining rules). Else, 0.		

Table B3-2

MATRIX DEFINITION RECORD STRUCTURE

Line	Variables	Definition	Format	Conditions
3	AID	Matrix identification code for operand matrix A used to calculate the matrix being defined.	4F10.0	Always include
	BID	Matrix identification code for operand matrix B used to calculate the matrix being defined.		
	NEXT	Matrix identification code for next matrix to be calculated/displayed.		
	ANORM	Value to be used when normalizing the matrix, if appropriate. Type of normalization, row, column, or total depends on the type of summation performed as specified in line 2.		
4	AMAT	Values to be stored in the data matrix being defined.	8F10.0	Values must be entered row by row. At most, 8 values per line Only valid when TYPE=1 (DATA). Use as many lines as necessary.
5	INDEX	VECTOR used in combining rules 4, 5, 16, 17, and 18. Refer to combining rules to determine number of elements required in VECTOR for the specified rule.	8I10	Only valid when METH=4, 5, 16, 17, or 18 At most, 8 values per line Use as many lines as necessary.

Table B3-2 (continued)

B.4 Example Model

For demonstration purposes, assume that the matrices in Table B4-1 are given as data. The task is to multiply the SYSTEM UTILITY matrix by the UTILITY WEIGHTS matrix element by element, sum each row of the resulting product, multiply the EFFECTIVENESS RATIOS matrix by the summation column, and normalize the resulting matrix so that the sum of all elements in the matrix is 100.

SYSTEM UTILITY

	Year 1	Year 2	Year 3	Year 4
Factor 1	10	20	30	40
Factor 2	5	10	15	20
Factor 3	1	2	3	4

UTILITY WEIGHTS

	Year 1	Year 2	Year 3	Year 4
Weight 1	1	2	3	5
Weight 2	2	3	4	5
Weight 3	2	3	4	5

EFFECTIVENESS RATIOS

	Model 1	Model 2	Model 3	Model 4	Model 5
Measure 1	2	4	6	8	10
Measure 2	10	9	8	[illegible]	6
Measure 3	5	5	4	6	6

Table B4-1

The intermediate matrices that would be required are:

WEIGHTED UTILITY BY YEAR - The product of SYSTEM UTILITY by the UTILITY WEIGHTS matrix with a summation column;

WEIGHTED UTILITY - A vector containing the single summation column computed in the WEIGHTED UTILITY BY YEAR MATRIX;

MODEL SCORES - The product of the column vector in the WEIGHTED UTILITY vector and the EFFECTIVENESS RATIOS matrix.

Table B4-2 shows the structure of this model with identification codes added:

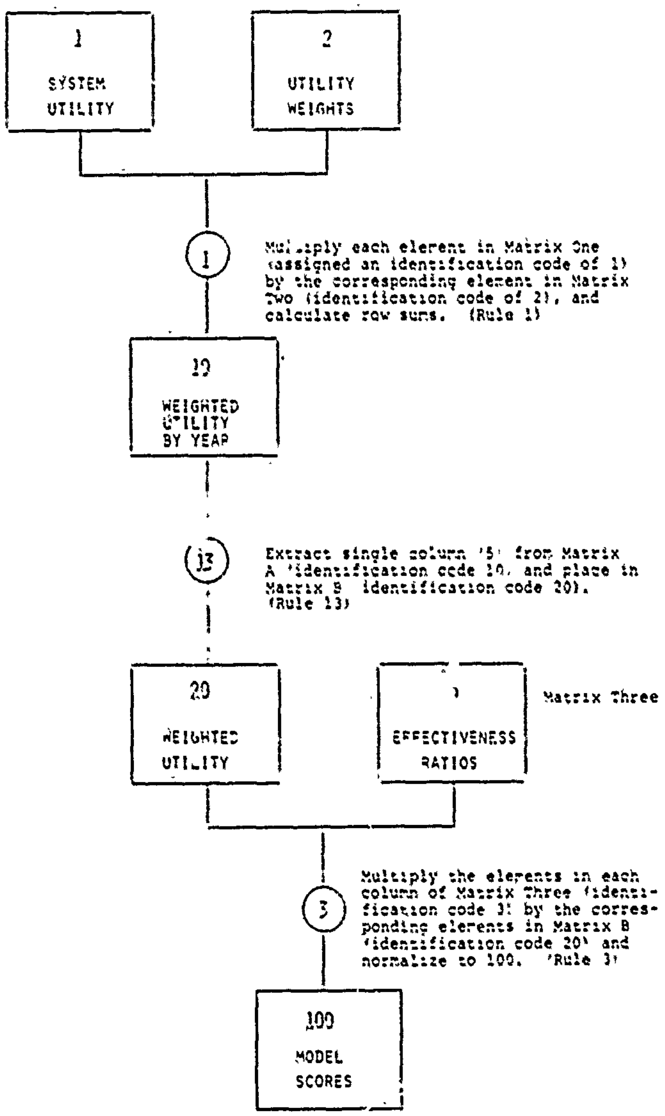


Table B4-2

Table B4-3 is an annotated list of the coding used in the Initialization Data File; Table B4-4 is an illustration of the results which would be produced.

CODE (Part 1) INITIALIZATION DATA FILE CODING

8	The number of label sets is 8
5, 7 Year 1 Year 2 Year 3 Year 4 Total	Label set 1 reserves 7 characters per label and has 5 labels.
3, 9 Factor 1 Factor 2 Factor 3	" " 2 " 9 " " " " " 3 "
3, 9 Weight 1 Weight 2 Weight 3	" " 3 " 9 " " " " " 3 "
3, 10 Utility 1 Utility 2 Utility 3	" " 4 " 10 " " " " " 3 "
3, 10 Measure 1 Measure 2 Measure 3	" " 4 " 10 " " " " " 3 "
6, 8 Model 1 Model 2 Model 3 Model 4 Model 5 Total	" " 6 " 8 " " " " " 6 "
4, 8 Score 1 Score 2 Score 3 Total	" " 7 " 8 " " " " " 4 "
1, 2	" " 8 " 2 " " " " " 1 "
Blank Line	Blank Label

Table B4-3

INITIALIZATION DATA FILE CODING

CODE (Part 2)	ANNOTATION
1, SYSTEM UTILITY	Matrix identification code of '1', title is 'SYSTEM UTILITY.'
3, 4, 1, 0, 0, 1, 2, 0	3 rows, 4 columns, type 1 (data) . . . Column label set is 1, Row label set 2.
0, 0, 2, 0	Next matrix is '2.'
10, 20, 30, 40	Row 1 data.
5, 10, 15, 20	Row 2 data.
1, 2, 3, 4	Row 3 data.
2, UTILITY WEIGHTS	Matrix ID code of '2,' title is 'UTILITY WEIGHTS.'
3, 4, 1, 0, 0, 1, 3, 0	3 rows, 4 columns, type 1 . . . Column label set 1, Row label set 3.
0, 0, 10, 0	Next matrix is '10.'
1, 2, 3, 5	Row 1 data.
2, 3, 4, 5	Row 2 data.
2, 3, 4, 5	Row 3 data.
3, EFFECTIVENESS UTILITY	Matrix ID code of '3,' title is 'EFFECTIVENESS RATIOS.'
3, 5, 1, 0, 0, 6, 5, 0	3 rows, 5 columns, type 1 (data) . . . Column label 6, Row label 5.
0, 0, 100, 0	Next matrix is '100.'
2, 4, 6, 8, 10	Row 1 data.
10, 9, 9, 7, 6	Row 2 data.
5, 5, 4, 6, 6	Row 3 data.

CODE (Part 3)	ANNOTATION
10, WEIGHTED UTILITY	Matrix ID code of '10,' title is 'WEIGHTED UTILITY.'
3, 5, 2, 1, 1, 1, 4, 0	3 rows, 5 columns, type 2 (calculated), Rule 1, Summation type 1, Column label set 1, Row label set 4.
1, 2, 20, 0	Operand A-Matrix 1, operand B-Matrix 2, Next Matrix-Matrix 20.
20, TOTAL UTILITY . . . 1	Matrix ID code of '20,' title is 'TOTAL UTILITY,' 1 in column 51 signifies a non-printing matrix. 3 rows, 1 column type 2 (calculated), Rule 13.
3, 1, 2, 13, 0, 8, 4, 5	Column label set 8, Row label set 4, NT-5 (column number for rule 13).
10, 0, 3, 0	Operand A-Matrix 10, Next Matrix-Matrix 3.
100, MODEL SCORES	Matrix ID code '100,' title is 'MODEL SCORES.'
4, 6, 2, 3, 3, 6, 7, 0	4 rows, 6 columns, type 2 (calculated), Rule 3, Summation Type 3, Column label set 6, Row label set 7.
3, 20, 0, 100	Operand A-Matrix 3, Operand B-Matrix 20, Normalize to 100.

Table B4-3 (continued)

SYSTEM UTILITY	Year 1	Year 2	Year 3	Year 4
Factor 1	10	20	30	40
Factor 2	5	10	15	20
Factor 3	1	2	3	4

(IMAGE 1)

UTILITY WEIGHTS	Year 1	Year 2	Year 3	Year 4
Weight 1	1	2	3	5
Weight 2	2	3	4	5
Weight 3	2	3	4	5

(IMAGE 2)

WEIGHTED UTILITY	Year 1	Year 2	Year 3	Year 4	Total
Utility 1	10	40	90	200	340
Utility 2	10	30	60	100	200
Utility 3	2	6	12	20	40

(IMAGE 3)

EFFECTIVENESS RATIOS	Model 1	Model 2	Model 3	Model 4	Model 5
Measure 1	2	4	6	8	10
Measure 2	10	9	8	7	6
Measure 3	5	5	4	6	6

(IMAGE 4)

MODEL SCORES	Model 1	Model 2	Model 3	Model 4	Model 5	Total
Score 1	3.5	7.1	10.6	14.1	17.7	53.0
Score 2	10.4	9.4	8.3	7.3	6.2	41.6
Score 3	1.0	0.1	0.8	1.2	1.2	5.4
Total	15.0	17.5	19.8	22.7	25.2	100.0

(IMAGE 5)

Table B4-4

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20. ABSTRACT (Continue on reverse side if necessary and identify by block number)

This report describes the development of a multi-attribute utility approach to the development of an initial model for evaluating alternative naval aircraft weapon system (NAWS) force mixes, with particular emphasis on the rather difficult problem of the assessment of inter-class tradeoffs of the utility of NAWS effectiveness. Using measures of NAWS effectiveness → next page

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SECURITY CLASSIFICATION OF THIS PAGE (When Data Entered) by considering not only military factors, but also relevant political and economic factors.

Global scenarios are used to characterize adequately representative future situations in terms of generic threat levels and associated NAWS mission requirements in six geographic areas covering the world. The NAWS are introduced in each scenario, and the utility of the effectiveness of each is determined in each scenario and is aggregated across scenarios by using appropriate scenario probabilities to yield an overall expected utility for each system. For a particular year, the net expected utility of a dynamic force mix is the sum of the expected utilities of the individual NAWS in the inventory of the force for that year and mix. This expected utility is calculated for each year/mix combination to yield utility profiles for alternative force mixes overtime. The utility model has been programmed and tested on a digital computer with an interactive graphic capability.

The multi-attribute utility approach has several advantages which enhance its suitability for the air mix evaluation problem. Very important is the use of factoral decomposition procedures, which are of particular benefit in the assessment of inter-mission trade-offs in the utility effectiveness. Also, the hierarchical structure which results from such an analysis provides an explicit and traceable logic, the complexity of which can be increased as the nature of the problem demands. Finally, computer implementation of the model on an interactive graphic terminal allows numerous, rapid sensitivity analyses which facilitate the model modification and thus enhance validity.